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AN X-RAY APPARATUS FOR THERAPEUTIC TREATMENTS

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X-ray treatment is still for the present one of the most important means of combating malignant growths. For such treatment there is a tendency to use also extremely hard rays, obtained with tensions of millions of volts, in order to get a more effective distribution of the dosage in the body. For institutions with ample funds at their disposal new and larger installations are being developed for this purpose. In the field of the more conventional apparatus, working with voltages up to some hundreds of kilovolts, development is, however, also proceeding apace: by the application of modern methods of construction efforts are being made to produce this apparatus in a form enabling the medical practitioner to apply X-ray treatment more quickly, more efficiently and with accurate doses. An example of such a modern design is the Philips "Compactix" therapeutic apparatus.

Introduction

The requirement usually made of X-ray apparatus for medical treatment is that there must be a high degree of freedom of movement of the beam of rays, so that they can be directed upon the patient from all sides. In the conventional arrangement the X-ray tube was therefore mounted on a stand which permitted various degrees of freedom of movement, and the high tension required was supplied to the tube from a fixed high-tension generator via flexible cables. During the last decade other therapeutic equipment has been developed, based on a different principle of construction, the high-tension generator and the X-ray tube being built together to form one unit. This unit, when mounted on a suitable stand, is likewise freely movable, whilst the constructionally difficult cable connection has been eliminated. In this article a description will be given of the "Compactix" therapeutic apparatus which has been built by Philips on this principle and which is intended for a tube voltage up to 200 kV_{max} with an average tube current up to 10 mA. *Fig. 1* gives a general view of the installation.

For extremely high tensions, say one million volts, the building together of the tube and the generator is the only practicable solution if one is to follow the now generally accepted principle of complete protection of the user against the high tension without sacrificing the freedom of movement of the beam. This principle of the building together of tube and generator was in fact first applied for very small X-ray units with relatively low tension and low power, constructed for certain diagnostic purposes [1]). With such a small apparatus the high-tension cables would have formed a far too large and heavy part of the whole. For installations with tensions up to 200 or 300 kV, which are generally used for the treatment of deep-seated tumours, however, both methods of construction, with and without cables, have their merits.

For the construction of the "Compactix" apparatus new means were sought for providing for insulation against high tension, cooling, and the protection of the user against scattered X-rays. The satisfactory solution found for these problems made it possible to build a tube and generator unit comparatively small in size and light in weight, so that an easily adjustable apparatus could be obtained which enables the medical

[1]) Such an apparatus was demonstrated already in 1933 by A. Bouwers. See A. Bouwers, Modern X-ray development, Brit. J. Radiology **7**, 21, 1934; further also Philips Techn. Rev. **6**, 225, 1941 and **10**, 221, 1949.

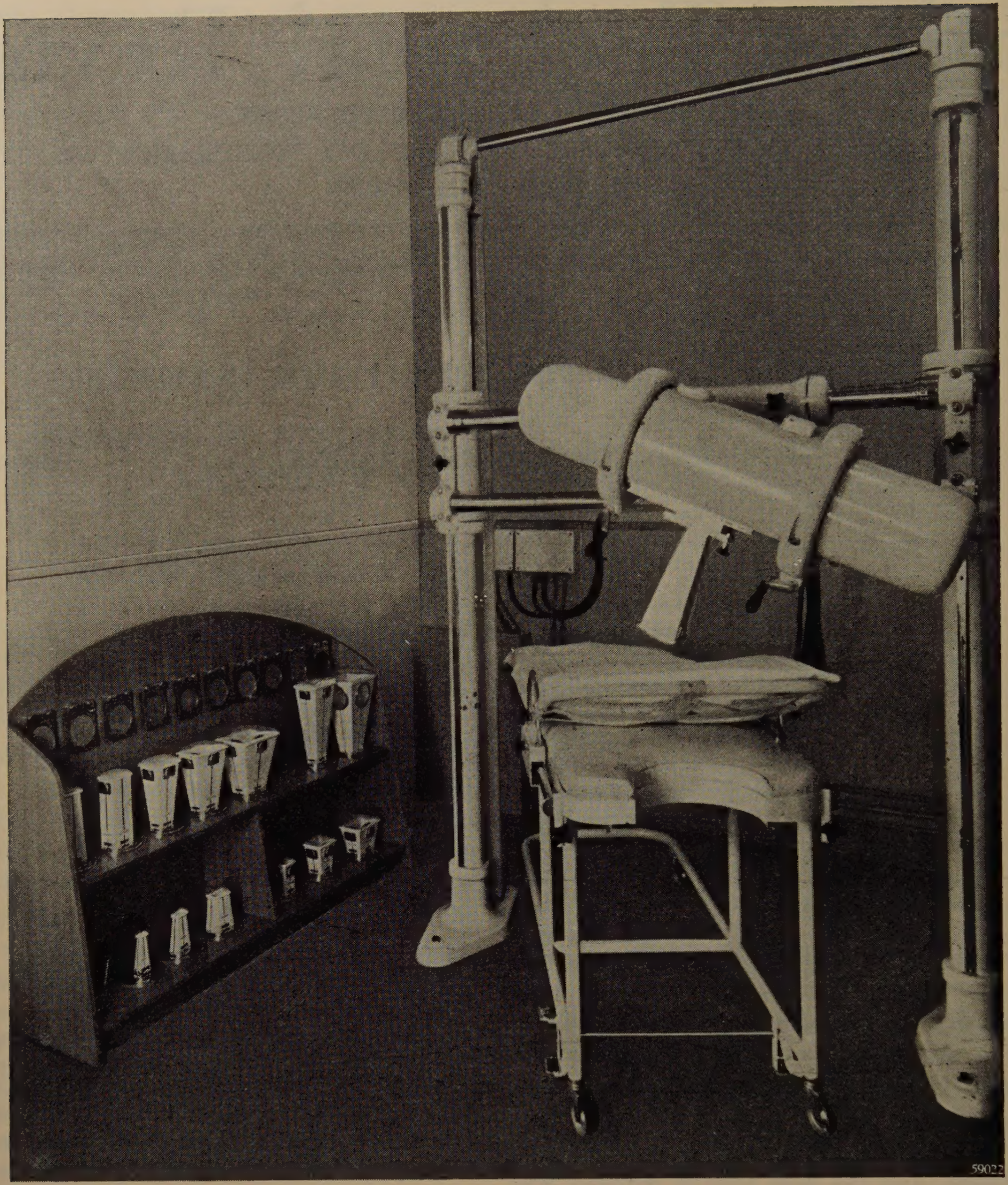

Fig. 1. The "Compactix" apparatus for X-ray therapy with stand and movable couch. In the cabinet on the left are the applicators and filters belonging to this apparatus. The apparatus is operated from a control desk in an adjoining room, where the operator can observe the patient through a lead-glass window.

practitioner to apply any treatment under the most favourable conditions.

In addition to the constructional problems mentioned, which will be dealt with when describing the X-ray tube and generator, some attention will also be devoted in the following pages to various new devices employed in the circuit of the apparatus, and the operating desk. The article will be concluded with some remarks about the accessories to be used, such as filters and applicators (cones), and about the distribution of dosage that can be obtained.

The X-ray tube

In *fig. 2* a photograph of the X-ray tube is reproduced; *fig. 3* is a somewhat simplified cross-sectional drawing in which also the most important dimensions are given. In the drawing one can see the tungsten target P which is mounted in the slanting face of the copper anode block and upon which the electrons emitted by the filament F are focused. It is in the comparatively sharp slope of the anode (anode angle $\alpha = 32°$, as compared with 15°-20° in most diagnostic tubes) that the specific character of therapeutic tube is imme-

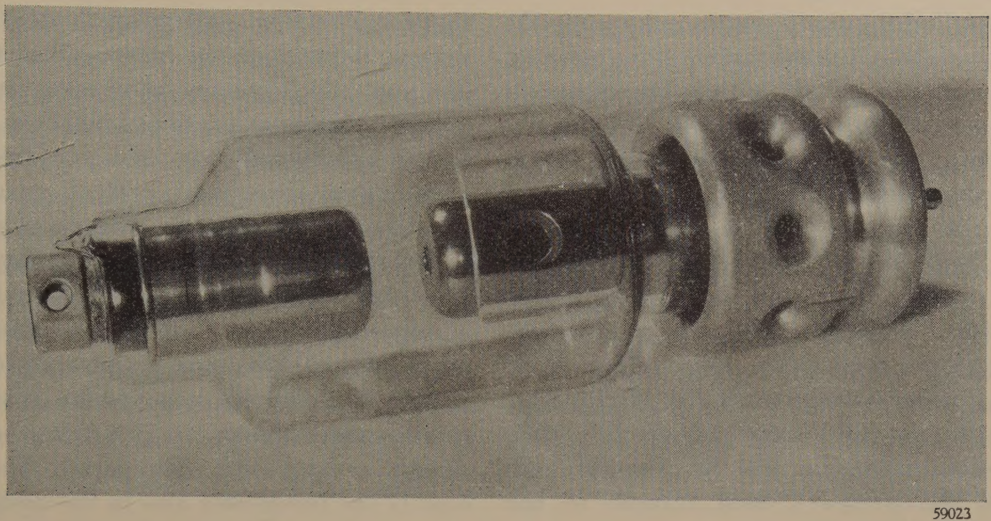

Fig. 2. X-ray tube of the "Compactix" apparatus. It is of hard glass and immersed in oil. The radiator on the right-hand end transmits the heat from the anode to the oil. The holes in the radiator allow the oil to flow through freely, so that there are no dead spots around the point where the anode is fused into the tube.

diately manifest: from the X-rays emitted from P in all directions it is thereby possible to make efficient use of a cone (R) with a large vertex angle, so that large fields can be irradiated at a relatively short distance.

The tube is immersed in oil in an earthed metal shield. It is due to the oil insulation that a tube of such a short length (short distance between the two poles) suffices for the high tension of 200 kV_{max}. The oil serves at the same time for cooling [2]). A radiator with a large surface area is mounted on the end of the anode protruding through the bulb. Around this radiator at a distance of 4.5 cm, inside the shield, are cooling-water spirals which are earthed and can therefore be connected to the water mains. Thus the heat developed on the focus and conducted through the anode body of the radiator is transmitted to the surrounding oil and then carried off by convection in the freely circulating oil to the water-cooled pipes. With this simple method of cooling a power of 1.4 kW can be applied continuously without any difficulty.

If, instead of letting the oil circulate freely, forced cooling is applied, by injecting the oil into the hollow anode, greater powers can be dissipated, but then there is the disadvantage of having to use an oil pump, with all its attendant noise, and in our case it was desired to avoid this.

[2]) This method of construction, applied to diagnostic tubes and also to a therapeutic tube resembling in broad lines that described here, has already been described in detail in this journal: J. H. van der Tuuk, Hard-glass X-ray tubes in oil, Philips Techn. Rev. **6**, 309-375, 1941.

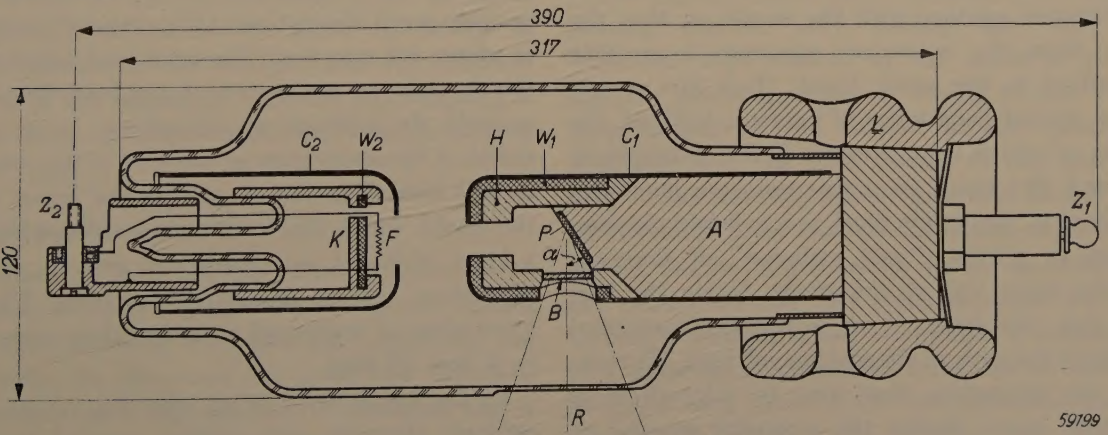

Fig. 3. Cross section of the X-ray tube (simplified). K cathode with filament F, A anode with tungsten target P, H anode hood for intercepting secondary electrons, B beryllium window allowing the X-ray beam R to pass through, W_1 tungsten hood and W_2 tungsten disc for absorption of the undesired X-rays, C_1 and C_2 polished chrome-iron caps, L radiator, Z_1 and Z_2 poles for connection to the high tension up to 200 kV_{max}.

The factor limiting the power in our case is the temperature of the oil at the surface of the radiator: if it should become too high then the oil would lose some of its insulating properties. The temperature of the anode at the point of fusion, which in other constructions sometimes sets the limit to the power, in our case remains well below the maximum permissible level of about 200 °C. Elsewhere, namely in the focus, the anode is of course hotter, notwithstanding the good heat conduction of the copper. The specific focus load, however, is comparatively small (30 W/mm²), so that the focus temperature also remains well below the permissible value (e.g. 500 °C). Therefore the problem of the primary heat transfer of the focus, which is of great importance in heavily loaded diagnostic tubes [3]), does not arise here. It is true that the specific focus load has been made greater for this tube than is usually the case with therapeutic tubes: the focus is comparatively small (5 mm × 10 mm, projected size 5 mm × 5 mm) so as to make the apparatus also suitable for the examination of materials, where the sharpness of the shadow pictures produced depends upon the size of focus.

For therapeutic purposes the size of the focus is not of primary importance, but here, too, limited dimensions of the focus are favourable because the volume irradiated can be more sharply defined (less penumbra round the edge of the diaphragm).

Mounted on the anode is an "anode hood" taking up the secondary electrons emitted by the focus on the anode. This protects the glass wall of the tube against an electron bombardment, so that no dangerous wall charges can arise, which may lead to disruption. The hood is made of copper and is in good thermal contact with the anode, so that the energy from the secondary electrons is quickly transmitted to the anode block. Over this copper hood a second hood made of tungsten is fitted, the purpose of which is to prevent X-ray radiation in undesired directions. Over this tungsten hood and the whole of the anode block is a polished chrome-iron cap to prevent "cold emission" of electrons from the outer wall of the anode during the half cycle that the latter is at a negative potential (the tube is fed with an alternating voltage). Furthermore, any impurities that may be released from the anode parts during the pumping process or while the apparatus is working, and which should be prevented from settling on the wall of the tube, are precipitated on the inner wall of this chrome-iron cap, which remains comparatively cold.

Something more has to be said about the absorption of undesired X-rays. This is a point that has always received a great deal of attention in the development of Philips X-ray apparatus. We would recall, for instance, the development of the "Metalix" tubes in 1923 [4]), when for the first time a construction was materialized which gave full protection of the user against X-rays emitted outside the effective cone (some years later the system was extended to give full protection also against contact with live parts). This idea was kept in the foreground also in the designing of the "Compactix" apparatus. In order to attenuate the 200 kV irradiation so that in the room where the operating staff is working the tolerance dose is not exceeded (in various countries a limit of about 0.05 to 0.1 roentgen per day is laid down), a screen of lead 4 to 5 mm thick is required round the source of the rays. Owing to its great weight such a thick layer of lead placed on the outside of the shield of the apparatus would hamper the easy handling aimed at. By applying an absorbing layer inside the tube itself at a short distance round the focus its weight has been reduced to a few hundred grams.

Of course lead cannot be used inside the tube, because at the temperature at which the tube is degassed it would melt. Absorption of the rays is therefore mainly brought about with tungsten, the atomic number of which (74) is only slightly lower than that of lead (82), so that the necessary layer of tungsten has about the same weight as an equivalent layer of lead. The copper of the anode hood and the chrome-iron of the outer cap do not provide much absorption as they are only equivalent to about 0.4 mm lead. The total lead equivalent of the three layers amounts to 4 mm lead. One cannot entirely do without an absorbent layer in the shield of the apparatus on account of the secondary X-rays formed in the oil and on the inner wall of the shield, which also have to be rendered harmless; a layer of lead 1 mm thick will provide sufficient protection against secondary radiation. The total absorption of undesired radiation then corresponds to 5 mm of lead.

In the anode hood is an opening to let in the primary electrons and another opening to let the effective X-ray cone pass out. The first opening

[3]) See for instance J. H. van der Tuuk, Philips Techn. Rev. 3, 292, 1938 and 8, 33, 1946.

[4]) See for instance A. Brouwers, A new X-ray tube, Physica, 4, 137, 1924.

allows not only a small part of the secondary electrons to escape but also undesired X-rays. The latter are absorbed by a tungsten disc mounted in the cathode for that purpose. The secondary electrons tending to escape through the second opening are stopped by a small disc of beryllium placed in this opening. Thanks to the very low atomic number (4) of this metal the useful X-rays are only very slightly weakened. In order that these rays should be weakened as little as possible on their further outward passage, the glass wall of the tube has been ground where the beam passes through, as may be clearly seen in figs 2 and 3. The surrounding layer of oil is also greatly reduced in the beam by a cap of "Philite" placed in the shield. Thus the inherent filtration of the apparatus (see the last chapter) is reduced to an equivalent of about 2 mm aluminium at 80 kV_{max}.

The high-tension generator

The desire to keep the high-tension generator as small and as light as possible led to the choice of an alternating current for supplying the X-ray tube. In the main the generator therefore consists only of a high-tension transformer and a filament transformer. The input voltage may be any mains voltage between 200 and 250 V, with a frequency of 40, 50 or 60 c/s.

In order to minimize as far as possible the difficulties of high-tension insulation, the X-ray tube is fed with a voltage which is symmetrical with respect to earth. For this purpose two separate high-tension transformers are employed, each of which, working in antiphase, supplies half the high tension (100 kV_{max}) to one pole of the tube. Owing to this arrangement it has been possible to divide the weight of the generator, one of the two transformers being placed at each end of the cylindrical tank in which the apparatus is mounted; see *fig. 4*. Thus the focus of the X-ray tube placed in the middle of the cylinder lies approximately in the centre of gravity of the whole apparatus, this greatly facilitating adjustments (see below).

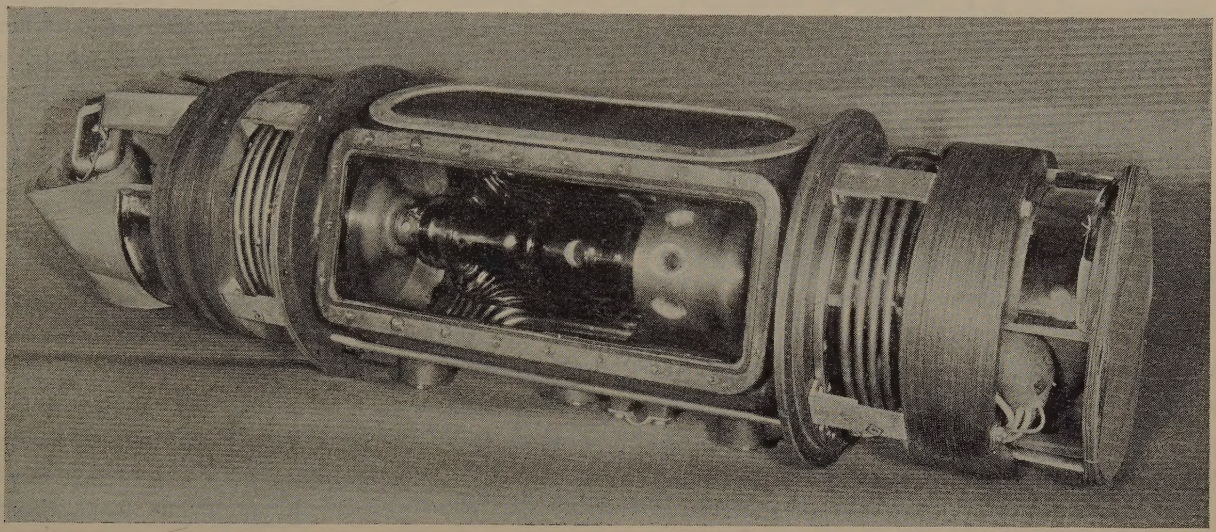

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Fig. 4. The X-ray tube, the high-tension transformers (on the right and on the left) and the filament transformer (on the extreme left) are built together into one unit which is mounted in a cylindrical tank. The tube compartment has a detachable lid. Cooling water spirals are contained in all three compartments.

The X-ray tube itself functions as rectifier, passing current only during the half cycle when the high tension at the anode is positive and the filament negative. Owing to the voltage drop caused by the current in the transformer windings, etc., the tube voltage in this half cycle may be up to 10% lower than that in the other half cycle. In order that the insulation requirements should not be unnecessarily severe on account of the non-conducting half cycle, so called inverse-voltage suppression is applied: a combination of a selenium rectifier and a resistor is connected in series with each of the two primary windings (see *fig. 5*). During the working half cycle the primary current flows through the selenium rectifiers with practically no resistance, whereas during the other half cycle it has to pass through the resistors, so that the voltage drop in the

resistors reduces the high tension generated.

These resistors perform at the same time an important function in the event of momentary disturbances in the X-ray tube. The stray self-inductance of the high-tension transformers together

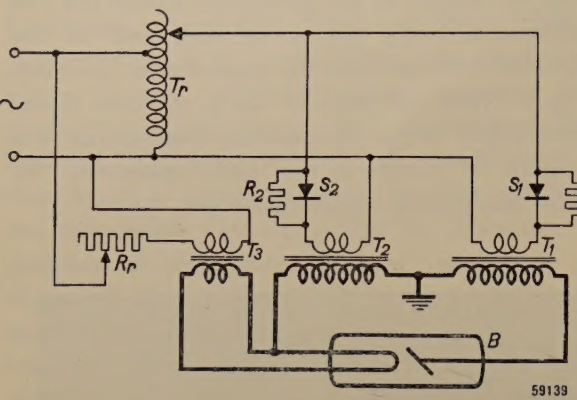

Fig. 5. Circuit of the high-tension generator. In the primary circuits of the two high-tension transformers T_1 and T_2 "inverse voltage suppression" has been applied (selenium rectifiers and resistors S_1, R_1 and S_2, R_2). B X-ray tube, T_3 filament transformer, T_r variable ratio transformer and R_r variable series resistor for adjusting respectively the tube voltage and tube current (to be discussed later).

with the earth capacitances, always present in the secondary windings, may form oscillatory circuits tending to produce dangerous overvoltages in the event of a surge in the tube. These overvoltages are strongly suppressed by the damping action of the resistors in the primary circuits.

The compact construction of the transformers has been made possible by using as insulating material paper impregnated with oil, a combination which has proved to be reliable and capable of withstanding heavy loads in the manufacture of capacitors and cables. One of the two high-tension transformers is illustrated in *fig. 6*. The circular shape of the yoke has been chosen so that the transformer can be placed in a cylindrical tank. The primary winding is made in two parts placed round the core on either side of the secondary winding; thus optimum use is made of the space available and at the same time a favourable distribution is obtained of the electric field between the windings of the secondary coil and the surroundings. The paper insulation is so shaped that the electric lines of force run as far as possible perpendicular to the surface of the paper. At the end of the secondary coil, to which the pole of the X-ray tube is connected, a metal screen is incorporated in the paper insulation (so-called potential screen) which helps to keep the maximum field strength between this high-tension pole and the earthed yoke small and at the same time reduces the capacitance of the outermost windings of the secondary coil with respect to earth. This latter point is of importance with a view to distributing overvoltages arising from possible tube disturbances evenly over the secondary winding.

From fig. 4 and the simplified cross-sectional drawing in *fig. 7* it may be seen how the transformers and the X-ray tube are located in the tank. The compartment for the tube formed by a central casting of light metal is entirely separated from the two adjacent compartments containing the transformers. As a result of this separation of the compartments the oil for the transformers is not called upon to help in carrying off the heat from the X-ray tube and thus is kept cooler, whilst when the X-ray tube reaches the end of its useful life it can be replaced without the transformer oil being exposed to the air.

In this case the problem of the thermal expansion of the oil has been solved in the following way. The oil in the tube compartment is able to expand on account of an oil-proof rubber diaphragm having been placed in one of the walls (to be seen at the top of fig. 4). The two transformer compartments are interconnected by a conduit passing along the outside of the tube compartment and thus need only one common expansion system. This has been provided by metal expansion bellows fitted at the anode end of the anode transformer compartment. The corresponding space in the compartment at the other end offers room for the

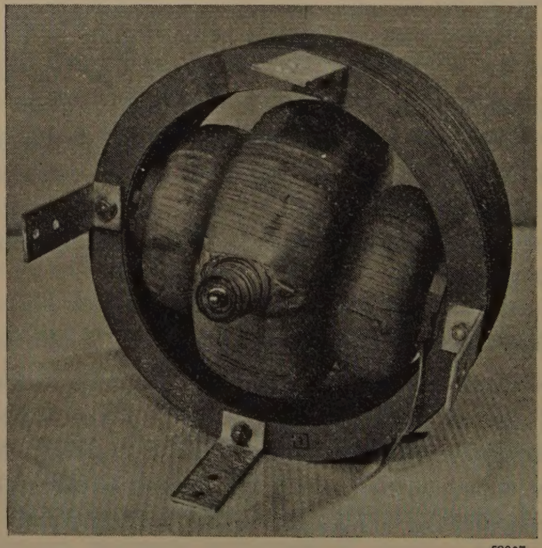

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Fig. 6. One of the two high-tension transformers, with circular yoke, oil-impregnated paper insulation, and a primary winding made in two parts and placed either side of the secondary winding. The high-tension pole of the secondary winding, which is connected to one of the poles of the X-ray tube, protrudes a little.

filament transformer, so that with the compact filling of the cylinder with the various parts the apparatus remains symmetrical.

Since a connection has to be made to the water mains for the cooling of the X-ray tube, it involves no extra complication to put some cooling spirals in the transformer compartments, this being advantageous for keeping the transformers as small as possible. The total losses in these transformers amount to about 200 W.

through an angle of 240°. In both these movements the whole apparatus, and also the focus of the X-ray tube, revolves about the centre of gravity.

The bridge part of the stand runs on ball bearings and is counterbalanced with weights moving up and down inside the vertical columns on which it runs, and can be moved in vertical direction. Further, the axis of the suspension arm can be moved in and out and the arm can be traversed horizontally along the tubes of the bridge.

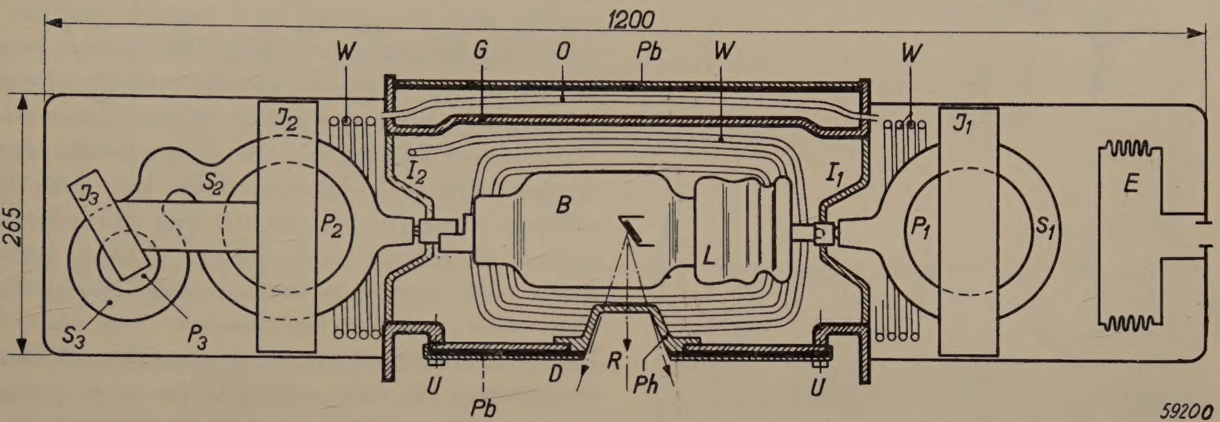

Fig. 7. Cross section of the tank of the "Compactix" apparatus (simplified). *G* central casting, *B* X-ray tube, I_1-I_2 "Philite" cups with lead-ins for the high tension. J_1, P_1, S_1 yoke, primary and secondary windings of the anode transformer, J_2, P_2, S_2 ditto of the cathode transformer, J_3, P_3, S_3 ditto of the filament transformer, *L* radiator, *W* cooling-water spirals in the three compartments, *O* connecting pipe between the two transformer compartments, *E* expansion bellows for the oil, *D* detachable lid fixed with screws *U*, *Ph* "Philite" cap where the X-ray cone *R* emerges, *Pb* lead jacket 1 mm thick in the shield.

Suspension of the apparatus

Fig. 1 shows the cylindrical tank suspended from a stand. The tank weighs in all 125 kg. (275 lbs). It is carried on an arm consisting of two rings joined together by two steel tubes. The arm is mounted in a bearing in the bridge of the stand in such a way that it can be turned around the horizontal axis. The movement around this transverse axis, which enables the tank to be set more or less upright, is brought about by means of a handle in one of the rings (the left-hand one in fig. 1). The cylinder can be turned 90° in the direction in which the cathode of the X-ray tube comes uppermost, and 45° in the opposite direction; it has been necessary to limit the latter movement in order to maintain adequate cooling of the anode by convection in the oil (the tube cannot be allowed to stand upright with the anode radiator uppermost). By means of a second handle (the right-hand one in fig. 1) the tank can be turned in the two rings about its own longitudinal axis

Fig. 8 shows how the tank can be moved, with the five degrees of freedom of movement mentioned. It can be seen that the practitioner is offered every desired possibility of adjustment. It is quite easy, for instance, to direct the rays in an upward direction (so-called under-couch treatment).

Stabilization, adjustment and measurement of voltage and current

The first essential for the success of X-ray treatment is exact dosage. To this end the practitioner must be able to rely upon the measuring instruments recording exactly the tube current and tube voltage, which determine the intensity and hardness of the X-rays generated, whilst it is also necessary that the current and voltage are not subject to fluctuations while the treatment is being applied.

Let us first consider the measurement. Connected to the earthed side of the secondary winding of each high-tension transformer is a moving-coil instrument which measures directly

the rectified current passing through the X-ray tube; see *fig. 9*. The object of using two meters for measuring this current is to avoid wrong dosage being applied in the event of one of the meters

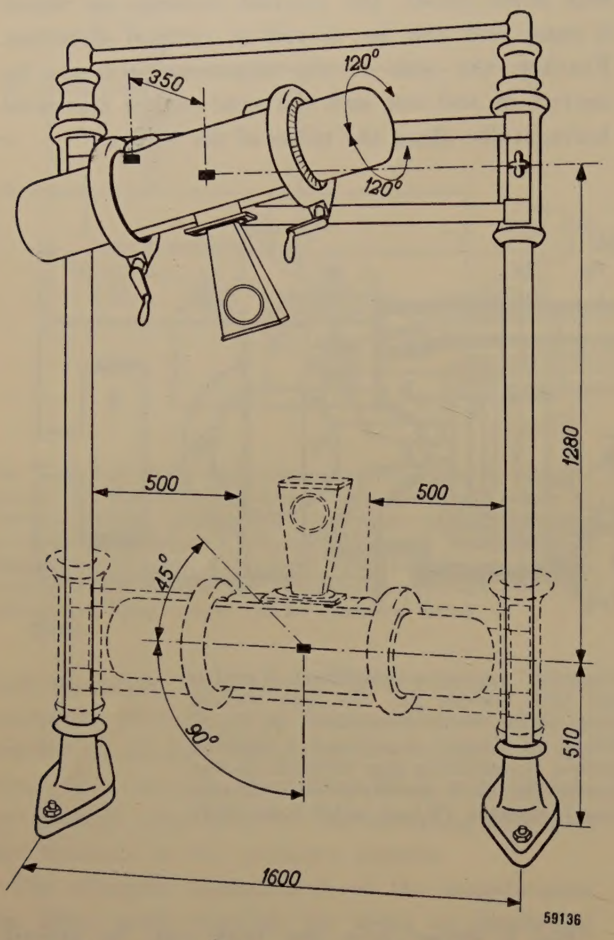

Fig. 8. Degrees of freedom of movement of the apparatus mounted on the stand: rotation about the longitudinal axis (240°), rotation about the horizontal transverse axis (135°), displacement in the direction of this transverse axis (350 mm), horizontal displacement perpendicular thereto along the bridge (1000 mm), vertical displacement (1280 mm). The position indicated in dotted lines is for irradiating in an upward direction.

becoming defective, a safety measure that is prescribed in several countries.

Direct measurement of the voltage across the X-ray tube is not possible in the high-tension part, so that only the primary voltage of the high-tension transformers can be measured; multiplication by the transformation ratio gives the secondary voltage that would arise under no load. This no-load voltage, however, is the sum of the actual tube voltage and the voltage drop in the transformers on load, the drop being proportional to the tube current. A direct indication of the tube voltage can be obtained, independent of variations due to the voltage drop, with the aid of a measuring circuit, as shown in fig. 9. Across the voltmeter kV is the primary voltage, reduced by a correction voltage produced by the small transformer T_4 connected to the resistor R_4. This correction voltage is proportional to the primary current from the high-tension transformers flowing through T_4, and is thus practically proportional to the tube current. Consequently, by properly adjusting R_4, the voltmeter can be calibrated direct in kilovolts applied to the tube.

The adjustment of the tube current and tube voltage to the values desired for the radiation is usually done by means of a variable resistor in series with the primary winding of the filament transformer and by means of a variable ratio transformer feeding the primary winding of the high-tension transformer (cf. fig. 5). In principle the same method has been followed here, but with the addition of means for stabilizing the adjusted values of current and voltage within narrow limits with respect to mains voltage fluctuations and other possible disturbances. One has to reckon with mains fluctuations up to 10%. Without stabilization the tube voltage varies in proportion to the mains voltage, and the tube current in proportion to a higher power of the mains voltage, owing to the strong temperature-dependence of the emission of the filament. Furthermore, the emission may also vary to a certain extent in consequence of the filament absorbing impurities that may be released from the anode. This goes to show how important it is to have a properly stabilized current and voltage, the more so when it is borne in mind that the intensity of the radiation, which is in fact the point at issue, is proportional to the tube current and roughly proportional to the square of the tube voltage.

As regards the tube current, the stabilizing system employed corresponds in principle to one that has already been previously described [5]). The "resistance" of a pentode (ratio of anode voltage to anode current) is taken up in the primary circuit of the filament transformer via an isolating transformer; see fig. 9. This resistance is dependent upon the control-grid voltage. The voltage drop produced across the resistor R_5 by the current passing through the X-ray tube, reduced by a highly constant reference voltage E_0, is applied to the control grid. Thus any fluctuation in the tube current reacts via the pentode upon the filament voltage of the X-ray tube, and in such a direction and to such an extent that the mean

[5]) Philips Techn. Rev. **8**, 8, 1946.

tube current is kept constant within about 1%. (Actually the voltage across the resistor R_5 consists of pulses, due to the X-ray tube being fed with an alternating current. Before being applied to the control grid of the pentode, however, this pulsatory voltage is smoothed by an R-C circuit, not shown in the illustration. Thus the stabilization acts only upon the mean value of the tube current.)

for feeding the high-tension transformers. A servo-mechanism causes the motor to rotate in one direction or the other according to whether the tube voltage is higher or lower than a predetermined value. How this regulating circuit works can be explained with reference to fig. 9. Two normal resistors and two small incandescent lamps form the four branches of a bridge circuit.

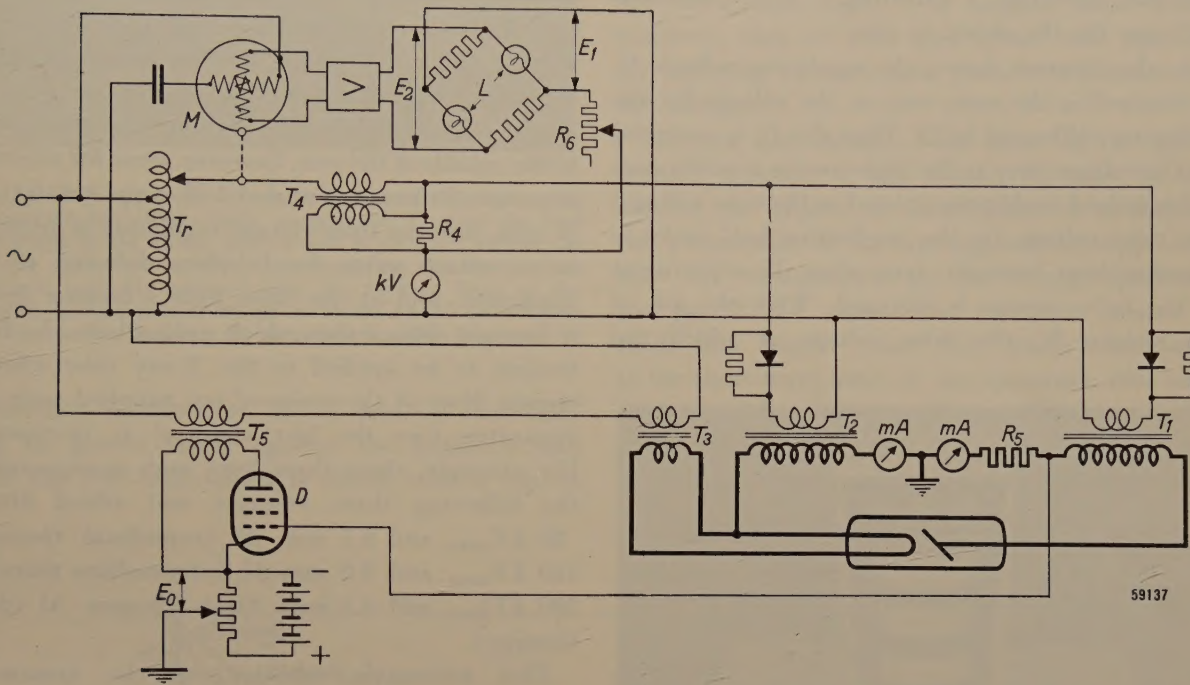

Fig. 9. Circuit diagram for measuring, controlling and stabilizing the tube current and tube voltage. The tube current is measured with the two moving-coil meters "mA", the tube voltage with the voltmeter "kV" calibrated in kilovolts.

For stabilization of the tube current: D pentode, the "resistance" of which is connected in series with the filament transformer T_3 via the isolating transformer T_5; R_5 resistor across which the tube current sets up a voltage which is applied to D as control-grid voltage; E_0 adjustable reference voltage, for the sake of simplicity indicated as being derived from a battery (actually it is supplied by a small rectifier with stabilized output connected to the mains).

For stabilization of the tube voltage: L two incandescent lamps which together with two normal resistors form a bridge, E_1 input voltage on this bridge proportional to the tube voltage, E_2 output alternating voltage the phase of which is reversed when E_1 passes through the rated value, M asynchronous motor driving the brush gear of the variable-ratio transformer T_r for the primary voltage of the high-tension transformers T_1 and T_2.

The reference voltage E_0 having been made adjustable, it is possible to determine at what voltage across R_5 equilibrium is reached, and thus by means of the same mechanism the desired control of the tube current is obtained, this being adjusted as desired between 2 and 10 mA.

For stabilizing the high tension somewhat stronger measures than a single electronic valve are needed. For this purpose a small asynchronous motor is employed for driving the brush gear of the above-mentioned variable ratio transformer

The lamps function as resistors having a value which varies steeply with the applied alternating voltage E_1 (owing to the fairly large fluctuation of the filament temperature). As a result the bridge is only balanced when E_1 has a certain value, that is to say, at a certain value of the tube voltage; the output voltage E_2 is then zero. When the value of E_1 varies, an alternating voltage $E_2 \neq 0$ is obtained which, when E_1 is too high, is in anti-phase with the voltage obtained at too low a value of E_1. The voltage E_2 is amplified and applied

to one of the two field windings of the afore-mentioned asynchronous motor, whilst the other field winding is connected to the mains (via a capacitor for the required phase shift). Since the direction of rotation of the motor is reversed when the phase of E_2 changes, by means of this mechanism any deviation of E_1 from a predetermined value can be made to bring about a counteracting change in the variable ratio transformer. In practice it has been found possible to stabilize the high tension in this way to within a variation of 0.9%, which is sufficient for the object in view.

As the diagram shows, the regulating voltage E_1 is obtained in the same way as the voltage for the voltmeter calibrated in kV. Thus also E_1 is corrected for the voltage drop in the high-tension transformers and is indeed made proportional to the tube voltage. The tube voltage (in the conducting half cycle) is therefore kept constant, even when the adjustment of the tube current is changed. With the aid of the resistor R_6 the tube voltage at which the regulating circuit comes to rest can be adjusted as desired between 80 and 200 kV_{max}.

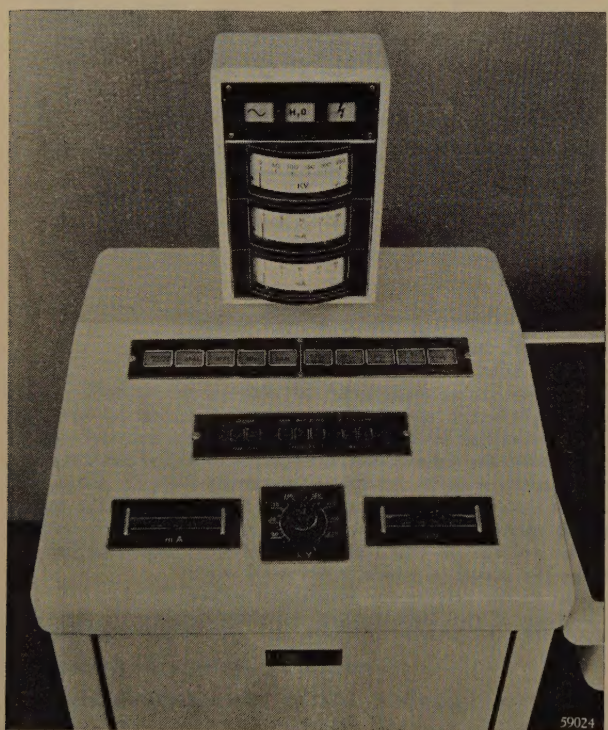

Fig. 10. Top view of the control desk. Bottom row of controls: Control disc for the tube current (on the left), control knob for the tube voltage (in the middle), and on the right a control disc which is coupled direct to the variable ratio transformer for the tube voltage but which normally does not need operation by hand, Next row: On the left keys for switching the mains voltage on and off, and on the right keys for switching the high tension on and off, as also for selecting three standard ray qualities. Upper row: 10 pilot lamps indicating which filter is in use. In the "meter tower": kV-meter, two mA-meters and three signals with green, white and red lights to indicate respectively whether the mains voltage, the water cooling and the high tension are switched on.

The circuit described in this chapter, together with some other accessories, is contained in a control desk, a close-up view of which is given in *fig. 10*. The functions of the various knobs, meters, etc. seen on the top panel are explained in the legend. There is one particular point to be discussed which is connected with the stabilization of the tube voltage. In the middle of the panel on top of the desk is a row of keys, of which the first two from the left serve for switching the mains voltage on and off, whilst the last two on the right serve for switching the high tension on and off, which can then be freely chosen. The three keys in the middle of the row, however, serve for selecting any one of three standard X-ray qualities; in each case the tube-voltage regulation is adjusted to a certain value fixed before delivery of the apparatus, and at the same time a locking device is brought into action which only allows the high tension to be applied to the X-ray tube when a certain filter of the series of ten supplied with the apparatus (see the last chapter) is interposed. For example, these three keys may correspond to the following three voltages and added filters:

80 kV_{max} and 0.5 mm Al (superficial therapy)
140 kV_{max} and 3.0 mm Al (intermediate therapy)
200 kV_{max} and 0.5 mm Cu + 1.0 mm Al (deep therapy).

This automatic selection of the treatment technique has only been made possible by the automatic stabilization of the tube voltage described here. It may be very convenient for the operator, since he already has to determine so many variables for each treatment: tube voltage, tube current, irradiation time, filter, focus-skin distance, size of the field to be irradiated, and the direction of the beam with respect to the object.

Applicators and filters

The focus-skin distance and size of field chosen can easily be obtained with the aid of one of the series of 15 applicators (cones), supplied with the installation (see fig. 1), two of which are shown in *fig. 11*. Such an applicator [6]) contains, in the circular flange with which it is attached to the apparatus, a lead diaphragm which confines the useful beam to the dimensions required for the desired field. The applicators have three different lengths corresponding to the most commonly used

[6]) The applicators have been made according to the directions of Dr. G. J. van der Plaats, Maastricht.

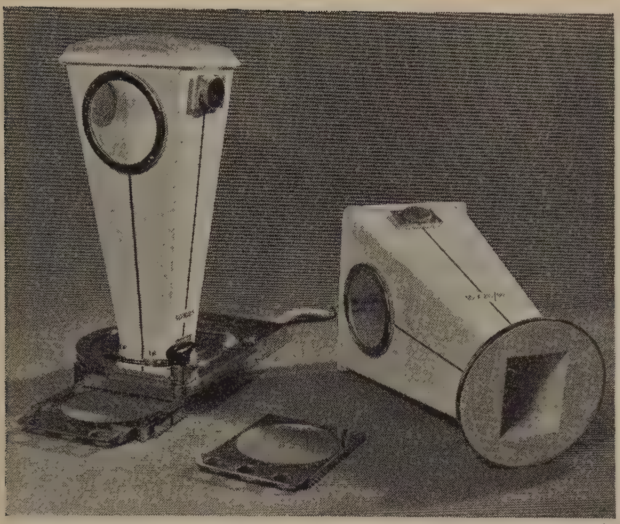

Fig. 11. Two applicators, both for a focus-skin distance of 50 cm; the one on the right, turned over to show the lead diaphragm in the flange, gives a field of 15 cm × 20 cm; the upright applicator on the left, attached to the filter-holder, which is normally screwed onto the tank in front of the window, gives a field of 10 cm × 15 cm. In the filter-holder is a filter pushed half-way in, whilst another filter lies beside it.

focus-skin distances of 30, 40 and 50 cm. They can be placed direct against the patient's sk.n with the free end, which is closed with a convex plastic cap; if necessary compression of the patient is used, the right focus-skin distance being retained. The vertex angle of the sides of each applicator is so chosen that every point of the field to be irradiated (and only of that field) faces the whole of the focus. Points of the penumbra of the diaphragm still face (through the wall of the applicators) part of the focus and would thus also be irradiated, though with reduced intensity. To avoid this the sides of the applicators are lined with lead. The largest have loteral windows, shut off with lead glass, and openings for inserting an ionization chamber for measuring the dosage.

Mention has already been made of the use of certain filters in the beam. As may be well known, the object of these filters is to increase the penetration of the rays applied, by suppressing the soft components in the X-ray spectrum; see *fig. 12*. Of course the radiation cannot be made any harder than that which corresponds to the short-wave limit of the spectrum, this being determined by the tube voltage. Moreover, with a given voltage one cannot choose too heavy a filter, because the filter also weakens the hard components

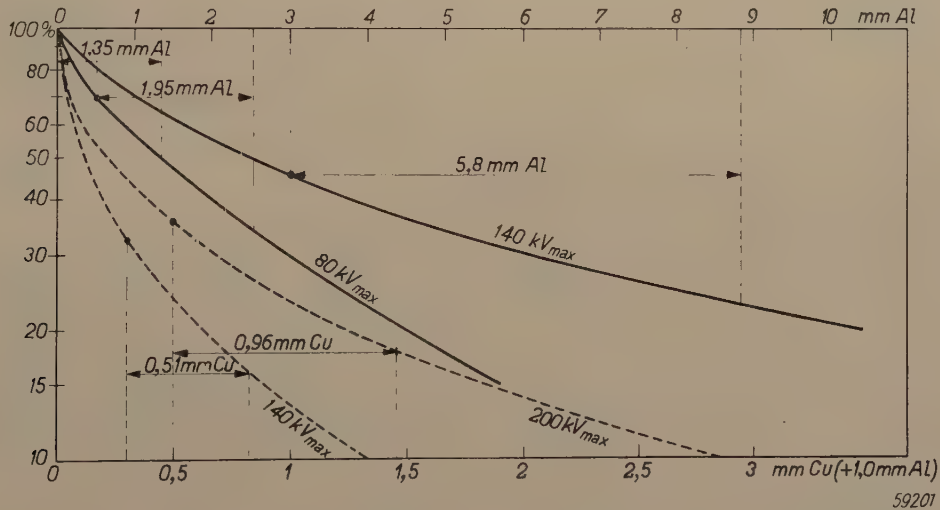

Fig. 12. When the rays from the "Compactix" apparatus, produced with tube voltages of 80, 140 and 200 kV_{max}, are passed through a layer of aluminium or copper their intensity is reduced according to the curves given (fully-drawn lines Al, dotted lines Cu + 1.0 mm Al). It is seen that by passing through the layer the rays are not only weakened but also become harder: the greater the thickness of the layer (filter) the smaller is the slope of the curve. The degree of penetration is denoted by the "half-value layer", i.e. the layer of Al or Cu which reduces the intensity of the already filtered rays to one half; up to 140 kV aluminium filters are used and the half-value layer is given in millimetres Al, whilst above 140 kV copper filters are used and the half-value layer is expressed in millimetres Cu. The non-filtered radiation from the "Compactix" apparatus produced with 80 kV_{max} has a "half-value layer" H = 1.35 mm Al (for different kinds of therapeutic apparatus this value varies according to the form of voltage applied and the inherent filtration). With an extra filter of 0.5 mm Al the value of H rises to 1.95 mm Al. With 140 kV_{max} and a 3.0 mm Al filter H = 5.8 mm Al, with 410 kV_{max} and a 0.3 mm Cu + 1.0 Al filter H = 0.51 mm Cu. Finally, with 200 kV_{max} and a 0.5 mm Cu + 1.0 mm Al filter H = 0.96 mm Cu.

and the intensity must be kept sufficient. For each tube voltage, therefore, only a few of the series of normal filter values can be considered. For use with the "Compactix" apparatus a series of ten different filters are supplied with which all the usual combinations of voltages (up to 200 kV) and filters can be obtained; see the table given below.

Table I. Filters for the "Compactix" apparatus. A filter has to be inserted for any treatment, even when for a particular treatment the "inherent filtration" of the apparatus would be considered sufficient; in the latter case filter number 1 has to be used, thus avoiding the possibility of the user forgetting to select a filter and thus by accident working without an extra filter. Filter number 10 is used for cutting off the radiation when the operating staff have to be near the apparatus while it is working. Filter No. 9 is the well-known Thoraeus filter, which has a smaller total absorption than an equivalent copper filter, as regards penetration of the rays.

No.	Composition and thickness
1	0.0 mm —
2	0.5 mm Al
3	1.0 mm Al
4	2.0 mm Al
5	3.0 mm Al
6	0.3 mm Cu + 1.0 mm Al
7	0.5 mm Cu + 1.0 mm Al
8	1.0 mm Cu + 1.0 mm Al
9	0.4 mm Sn + 0.25 mm Cu + 1.0 Al
10	5.0 mm Pb

Each filter is in a metal frame which slides into the slot of the filter-holder (see fig. 11). This frame, which is screwed onto the tank window, contains a click-knob mechanism which holds the filter frame in place when it is pushed in (against a pressure spring) or releases it when the knob is pressed. Further the filter-holder contains a set of contacts which are closed by the filter frames in different combinations and which perform two functions: firstly, the interlocking of the high tension, which cannot be switched on if one should have forgotten to insert a filter; secondly, the signalling to the control desk, each filter causing one of a row of ten pilot lamps to light up so that the operator can see which filter has been inserted.

We shall briefly explain the influence of the penetration of the rays (ray quality). When treating affections of the skin one has to save the underlying tissues and thus use soft rays which are almost entirely absorbed in the outermost layers of the body. For this superficial therapy one therefore chooses the lowest voltage, 80 kV_{max}, without filter, or, to be more exact, with filter No. 1, which does not contain any absorbent material, so that only the inherent filtration of the apparatus is operative. On the other hand, when treating deep-seated tumours hard rays are desired in order to get a reasonably large "depth dose", that is to say a high ratio of the intensity at the given depth underneath the skin to the intensity on the skin itself (in normal cases, owing to the absorption in the body and the fact that the intensity decreases according to the square of the distance as the latter becomes shorter, this ratio of intensity is less than 1). For such a case of deep therapy, therefore, one will choose a high tube voltage and a heavy filter, higher and heavier according to the depth at which the object lies below the skin. The obvious question is what improvement is reached in the depth quotient with increasing penetration of the rays. An answer to this question is given in *fig. 13*, where the depth dose

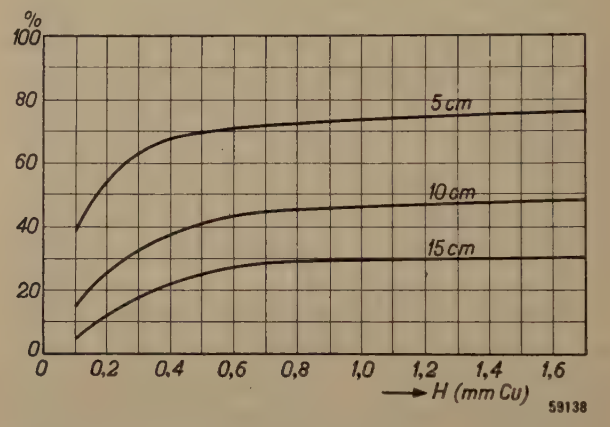

Fig. 13. The depth dose at three different depths underneath the skin as a function of the half-value layer H of the radiation. The focus-skin distance, which affects the depth dose according to the square of the decrease in intensity, is taken here to be 50 cm. The size of the field likewise affects the depth dose, since the secondary radiation at depths comparable with the field dimensions tends to equalize the intensity; these curves were plotted for a field of 400 cm². (Derived from L. Greber and K. Nitzge, Tabellen zur Dosierung der Röntgenstrahlen, Urban & Schwarzenberg, Berlin and Vienna, 1930.)

at three different depths is plotted as a function of the penetration for a certain focus-skin distance and a certain size of field. As measure for the hardness use has been made of the "half-value layer" defined in the legend of fig. 12. We see that up to about 0.8 mm Cu the depth dose rises sharply. With higher half-value layers the further gain in the depth dose is relatively little and of scarcely any consequence compared with the much greater gain that can be obtained in many cases by compression of the tissues, thus artificially

reducing the depth of the tumour. The maximum half-value layer that can be reached in practice with the "Compactix" is 0.96 mm Cu, obtained with 200 kV_{max} and a filter of 0.5 mm Cu + 1.0 mm Al, whereby the dosage rate with 10 mA and at a distance of 50 cm amounts to 20 roentgen per minute.

Only with tube voltages of an entirely different order, for instance of some millions of volts, essentially greater depth doses, even considerably greater than 1 can be obtained. The secondary X-rays and electrons generated in the human body, and which contribute towards the total dosage, become more and more directed forward according as the tube voltage is increased. Thus in the dosage curve, plotted as a function of the depth below the skin, a maximum is found at a certain depth. Such a maximum is already to be found at voltages of 200 kV but it is still little pronounced and lies at no more than about 1 cm below the surface of the skin; with very high voltages the maximum is fairly high and may come to lie at depths of 10 cm or more.

Summary. A description is given of the "Compactix" apparatus for X-ray therapy, which works with alternating voltages up to 200 kV_{max} and a tube current up to 10 mA. The high-tension generator is mounted together with the X-ray tube in a cylindrical tank 1.20 m long and weighing 125 kg (275 lbs). The tank is mounted on a stand which permits five degrees of freedom of movement and is easy to adjust for any type of treatment. Some of the constructional features are: separation of the high-tension transformer into two units for 100 kV placed at either end of the X-ray tube, so that the focus of the tube lies in the centre of gravity of the tank; there are three separate compartments in the tank, for the tube and the two transformers; the tube is insulated and cooled with freely circulating oil; the transformers are insulated with paper impregnated in oil; the oil in all three compartments is cooled by means of earthed cooling-water spirals which are directly connected to the water mains, thus dispensing with oil pumps or suchlike; the operator is fully protected against X-rays outside the effective applicator by a tungsten hood on the anode and a layer of lead 1 mm thick in the shield, with a total lead equivalent of 5 mm lead; high-tension transformer supply with "inverse voltage suppression"; tube-voltage measuring with automatic correction for the effect of the tube current; stabilization of tube current and tube voltage within about 1%, with special regulating circuits directly controlled by the current or the voltage; on the control desk, in addition to the normal current and voltage regulators, there are three keys for selecting three standard ray qualities, and signalling of the filter in use. Supplied with the apparatus is a series of 15 applicators, making it easy to limit the focus-skin distance and the size of field to be irradiated, and also a series of 10 filters. The maximum half-value layer obtained with a tube voltage of 200 kV_{max} and the filter of 0.5 mm copper plus 1.0 mm aluminium amounts to 0.96 mm Cu. With a tube current of 10 mA the dosage intensity at 50 cm distance is then 20 roentgen per minute.

Erratum

In the article by H. Rinia, D. Kleis and M. van Tol, Experimental transmitting and receiving equipment for high-speed facsimile transmission, I. General, published in Philips Techn. Review **10**, 189-195, 1949 (No. 7) the term photostat paper was erroneously mentioned on page 193; this should read dye-line paper.

A MILLIVOLTMETER FOR THE FREQUENCY RANGE FROM 1000 TO 30 × 10⁶ c/s

by H. J. LINDENHOVIUS, G. ARBELET and J. C. van der BREGGEN.

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For taking measurements of electrical apparatus in which voltages of widely divergent amplitude and frequency occur, such as in radio transmitters and receivers, carrier-telephony installations, etc., there is need for a voltmeter of a high but reducible sensitivity and having a frequency range extending from audio-frequencies to radio-frequencies of some tens of Mc/s. The measuring instrument described here, which in essence consists of a variable attenuator, an amplifier, a rectifier and a moving-coil meter, has been designed to provide for this need.

For measuring alternating voltages according to a system which has been known for a long time the voltage is rectified (with the aid of a diode or a crystal detector) and this rectified voltage is measured with a moving-coil instrument. One of the advantages of such a system is that within very wide limits the reading can be made independent of the frequency; steps can be taken, for instance, to cover a frequency range from 20 c/s to about 500×10^6 c/s. On the other hand, however, meters working according to this system are relatively insensitive: for full-scale deflection a voltage is required of the order of at least 1 V (we shall revert to this point later). It is obvious that in order to be able to measure also smaller voltages an amplifier should be connected in front of the meter. This idea has been put into practice in instruments which give full deflection at only a fraction of 1 mV, but with the instruments so far placed on the market this very high sensitivity has been obtained at the cost of the frequency range, which then covers a bandwidth of only about 10,000 c/s.

Here an instrument will be described (type GM 6006) in which the amplifier is of such a construction as to pass a very wide frequency range (from 1000 to 30×10^6 c/s), whilst the full deflection is obtained with an input voltage of 1 mV. The amplification amounts to about 1500 and in order to keep it independent of the frequency in such a wide frequency range the amplification per stage has to be small, as will be seen later on, so that a rather large number of stages are required. This involves problems such as stabilization of the amplification, reduction of noise and the designing of a simple device with which the instrument can be calibrated at any moment.

Fig. 1 is a photograph of the instrument in question; it is provided with an attenuator — to be described farther on — which makes it possible to measure voltages up to 1 kV.

The amplifier

Upper limit of the frequency range

The amplifier has six stages, each equipped with an EF 42 pentode. Except for some minor points the first five stages are identical. The sixth stage, the load of which differs from that of the preceding ones and which is therefore built differently, will not be considered for the moment.

In *fig. 2a* a diagram is given of one of the first five amplifying stages (omitting the direct voltage sources). In fig. 2*b* we have the same diagram but showing only those elements which essentially determine the amplification at high frequencies, viz: the valve, the anode resistor R, the reactance coil L (the object of this will be shown later), and the capacitances C_1 and C_2 consisting respectively of the output capacitance of the preceding valve and the input capacitance of the following valve, plus some stray capacitance.

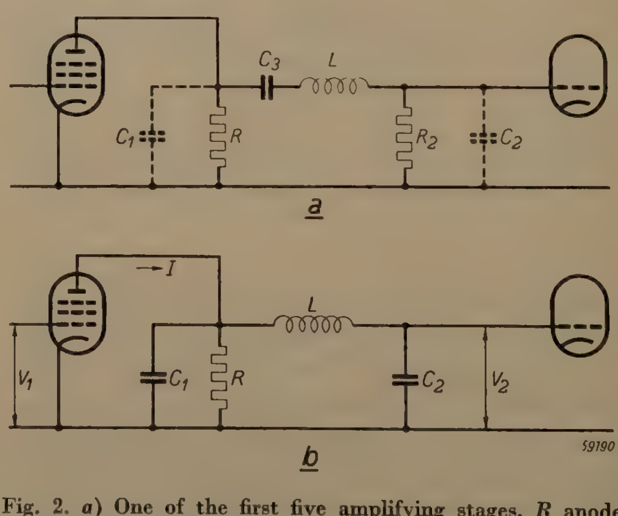

Fig. 2. *a*) One of the first five amplifying stages. R anode resistor. R_2 = grid resistor, C_1 = output capacitance of the preceding valve plus some stray capacitance, C_2 = input capacitance of the following valve plus some stray capacitance, C_3 = coupling capacitor, L = reactance coil for raising the upper frequency limit. *b*) The same but omitting the elements which do not affect the amplification at high frequencies.

Fig. 1. Millivoltmeter type GM 6006, with the attenuator in the foreground. On the control panel from left to right: terminal sockets for an input voltage of max. 1 mV, change-over switch, plug socket to which the attenuator is connected, pilot lamp, mains switch, and terminal sockets from which a voltage can be taken (max. 0.5 V) that is 500 times as great as the input voltage. The change-over switch has three positions: (1) "Direct" (attenuator out of action, for voltages up to 1 mV), (2) "10^{-3}-10^{3} V" (with attenuator) and (3) "Contr." (calibrating position).

The top and middle scales differ mutually by a factor $\sqrt{10}$; it depends upon the position of the attenuator which of these scales has to be used and by how many factors of 10 the reading has to be multiplied to give the voltage to be measured in millivolts or volts. The bottom scale is calibrated in decibels; 0 db lies at 0.775 V (corresponding to 1 mW in a resistance of 600 ohms).

For the case where $L = 0$ the relation between the alternating voltage V_2 (with angular frequency ω) at the grid of the right-hand valve and the anode alternating current I of the left-hand valve (V_2 and I in absolute values) is

$$V_2 = \frac{R}{\sqrt{1 + (\omega C_p R)^2}} \cdot I,$$

where $C_p = C_1 + C_2$.

Taking V_1 as representing the alternating voltage at the grid of the left-hand valve and S the mutual conductance of that valve, then $I = SV_1$, so that when we put $\omega C_p R = x$ the amplification V_2/V_1 of this stage is:

$$\frac{V_2}{V_1} = \frac{SR}{\sqrt{1 + x^2}} \quad \ldots \ldots \ldots \quad (1)$$

In *fig. 3* the dotted curve represents $V_2/V_1SR = 1/\sqrt{1 + x^2}$ as a function of x, the latter being a measure of the frequency. It shows the well-known phenomenon of the amplification diminishing as the frequency is raised, due to the capacitance parallel to R.

Allowing for a moment a drop of say 5% per stage (which for six stages means a drop of 27% in the total amplification), then the dotted curve in fig. 3 shows that this limit is reached at $x = \omega C_p R = 0.33$. To get a high upper frequency limit C_p and R have to be kept small. Now even with a proper choice and judicious mounting of the components C_p cannot be made smaller than about 20 pF, whilst the value of R is governed by the nominal amplification per stage ($= SR$) and the mutual conductance. The latter, in the case of the "Rimlock" pentode EF 42 employed,

amounts to a maximum of 9.5 mA/V, but with a view to having some reserve and the possibility of adjustment these valves are adjusted for $S =$ 8.0-8.5 mA/V. Thus for an amplification of say 3 per stage — a lower factor is not likely to be desired — an anode resistance of 370 ohms is

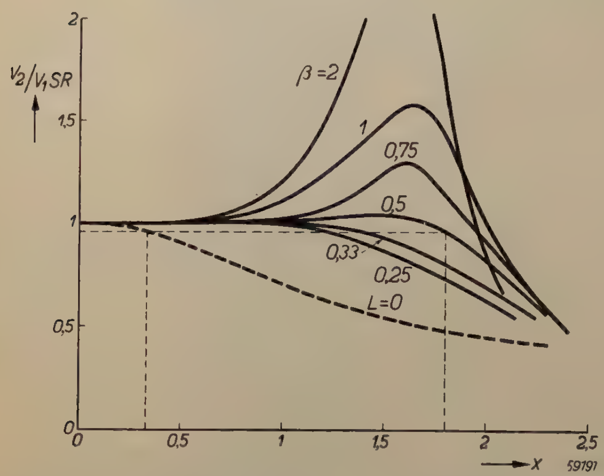

Fig. 3. V_2/V_1SR as a function of $x = \omega C_pR$. The dotted curve applies for $L = 0$ (formula (1), the full lines applying for L according to formula (3), with $\beta = C_1/C_2$ as parameter (formula (4)). On a certain scale these curves represent the amplification per stage (V_2/V_1) as a function of the frequency. The best characteristic is obtained with $\beta \approx 0.5$.

required. For the upper limit f_{max} of the frequency range we then find:

$$f_{max} = 0.33/(2\pi \times 20 \times 10^{-12} \times 370) \text{ c/s} \approx 7 \text{ Mc/s}.$$

A much higher frequency limit can be reached by adding a reactance coil with a suitably chosen inductance L (fig. 2). A simple calculation gives for the system shown in fig. 2:

$$\frac{V_2}{V_1} = \frac{SR}{\sqrt{(1-\omega^2LC_2)^2 + (1-\omega^2LC_s)^2 \cdot \omega^2C_p{}^2R^2}}, \quad (2)$$

where $C_s = C_1C_2/(C_1 + C_2) = C_1C_2/C_p$. Underneath the root sign we have, in addition to the constant 1, a term with ω^2, one with ω^4 and another with ω^6. If ω is made to rise from a low value then it is in general mainly the term with ω^2 which causes the greatest change in the denominator of (2). This term is:

$$(C_p{}^2R^2 - 2LC_2)\omega^2 .$$

It can be made to disappear by ensuring that $C_p{}^2R^2 = 2LC_2$, thus by choosing

$$L = \frac{C_p{}^2R^2}{2C_2} = \frac{1+\beta}{2} C_p R^2 , \quad . \; . \; . \quad (3)$$

where $\beta = C_1/C_2$. With this value for L eq. (2) becomes

$$\frac{V_2}{V_1} = \frac{SR}{\sqrt{1 + (\frac{1}{4} - \frac{\beta}{1+\beta})x^4 + \frac{1}{4}(\frac{\beta}{1+\beta})^2x^6}}, \quad . \; . \quad (4)$$

in which again $x = \omega C_pR$.

The full lines in fig. 3 represent V_2/V_1SR as a function of x for several values of the parameter β. It is seen that the amplification is now constant within 5% up to a value of x amounting to about 1.8 when $\beta \approx 0.5$. In other words, by a suitable choice of L and of C_1/C_2 one can reach, with the same nominal amplification per stage (3) and the same valves, a frequency limit more than five times as high as without the reactance coil L, namely about 38 Mc/s.

It is therefore a question of getting the right ratio of the capacitances C_1 and C_2. As already stated, these consist mainly of the output capacitance of the preceding valve (4.5 pF) and the input capacitance of the following valve (9.5 pF) respectively. To this must be added the capacitance of the valve-holder and of some components, so that we find that $C_1 = 7$ pF and $C_2 = 10$ pF. Thus the ratio $\beta = 7/15 = 0.47$ happens to be very favourable.

If, having regard to the tolerance, we do not go to the extreme value of x (≈ 1.8) but to 1.6, and putting the upper frequency limit at 30 Mc/s, then with $C_p = 7 + 15 = 22$ pF we get for R a valve of 400 ohms. For the corresponding value of L equation (3) gives $L = 2.5$ µH. The amplification per stage amounts to $SR = 3.25$.

We now come to the last stage, to which is connected — instead of the input of an EF 42 valve as in the preceding stages — the rectifying circuit, which has a much lower capacitance, viz. $C_2 = 3.5$ pF instead of 15 pF. If this stage were arranged in the same way as the preceding ones then we should have $\beta = 2$ (C_1 is again 7 pF) and, as can be seen from fig. 3, this would cause a high peak in the frequency characteristic. C_2 could be raised to 15 pF by shunting a small capacitor across it, thus making conditions equal to those in the preceding stages. However, there is a better method that can be followed, by means of which a greater amplification can be obtained. For this purpose the cricuit of the sixth stage is slightly altered: the coil L is placed in front of the resistor R, now denoted by R_1 (*fig. 4*, compare fig. 2). As can be readily checked, the formulae (2), (3) and (4) also hold for this case if C_1 and C_2 are interchanged (that is to say in (2) C_2 has to be

replaced by C_1; C_p and C_s remain unaltered, and β is to be taken as C_2/C_1). We can now again use the curves of fig. 3, particularly that having the most favourable shape ($\beta \approx 0.5$).

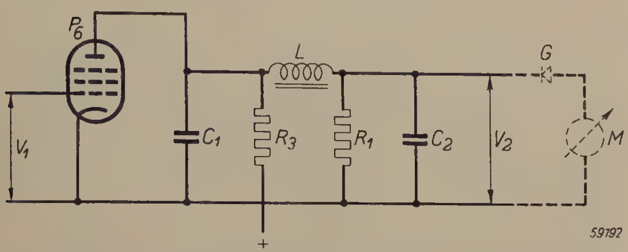

Fig. 4. To get a favourable value of β (fig. 3) in the network following the last amplifying valve (P_6) the reactance coil L precedes the resistor R, now termed R_1 (cf. fig. 2). R_3 = the resistor via which the anode is fed. The dotted lines indicate the rectifying unit (detector G, moving-coil meter M).

Taking again 1.6 as the highest value of x, then with 30 Mc/s as the frequency limit and $C_p = 7 + 3.5 = 10.5$ pF we find $R_1 = 800$ ohms. The amplification of the last stage, in which the EF 42 valve is also adjusted to a mutual conductance of about 8 mA/V, then amounts to $SR_1 \approx 6.5$.

In two respects the measures taken to keep the amplification constant up to the highest possible frequencies need supplementing.

1) The value of the capacitances C_1 and C_2, the ratio of which greatly affects the form of the frequency characteristics, cannot be governed very accurately, so that as a rule one stage will be working with a somewhat too high value of β and the other with a somewhat too low value. This could be remedied by adding trimmers. In practice it has been found that one trimmer suffices (across C_2 in the last stage). As an inevitable result C_p becomes somewhat greater than the above-mentioned value of 10.5 pF, and for that reason a smaller value has been chosen for R_1, viz. 510 ohms. Thus the amplification of the sixth stage becomes $SR_1 = 4.2$; the total amplification is therefore $3.25^5 \times 4.2 = 1500$.

It has also been found desirable to make the self-inductance L of the last stage adjustable. This coil has therefore been provided with a sliding core of "Ferroxcube", a material of high permeability and low losses [1]).

2) It has already been remarked in passing that a drop of 5% in the amplification per stage results in a drop of more than 25% in the total amplification (six stages). We shall now remove any impression that it may have been left at that. To avoid this drop, which would become particularly noticeable in the frequency range between 20 and 30 Mc/s, a coil with variable self-inductance L_1 has been incorporated in one of the anode circuits in series with the resistor R. The amplification of this stage is then approximately given by formula (4) if R is replaced in the numerator by $\sqrt{R^2 + \omega^2 L_1^2}$. The value of L_1 can be so chosen that as the frequency rises the numerator increases at a higher rate than the denominator, so that a rising frequency characteristic is obtained. Within a limited frequency range the decline in the amplification of the other stages can thus be compensated.

This measure has been taken in only one stage for the following reasons. If a self-inductance L_1 were to be placed in series with R in each of the six stages (it would then have to compensate a drop of only about 5% in the amplification) it would have to be so impractically small that it would hardly be possible to make these coils with the required accuracy.

This coil L_1 likewise has a sliding core of "Ferroxcube", with which the self-inductance can be adjusted to the optimum value.

The result of all this is to be seen from *fig. 5*, curve *I*, representing the deflection of the instrument as a function of the frequency with a constant input voltage. The small fluctuations in the characteristic between 10 and 30 Mc/s are due to small differences in the value of β in the various stages.

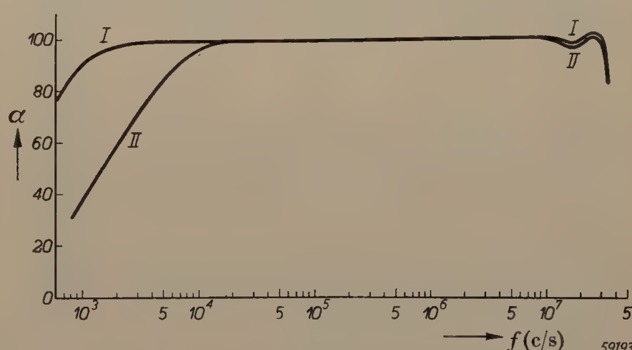

Fig. 5. The deflection α of the moving-coil meter as a function of the frequency f of the constant, sinusoidal, input voltage, *I* without attenuator, *II* with attenuator (in all positions).

The fact that at low frequencies the characteristic does not follow a horizontal line like that of fig. 3 is explained in the following paragraph.

Lower limit of the frequency range

The circuit elements essentially determining the shape of the frequency characteristic at low frequencies are — as will be seen — the coupling capacitors C_3 and C_4 and the resistors R_2 and R_3 (see *fig. 6*, obtained from fig. 2*a* by omitting the elements which are of no importance for the low frequencies, such as the capacitances C_1 and C_2 and the self-inductance L).

[1]) J. L. Snoek, Non-metallic magnetic material for high frequencies, Philips Techn. Review. **8**, 353-360, 1946.

C_3 and R_2 — a combination which occurs at the control grid of each of the six valves — form a voltage divider which gives for the ratio (in absolute value) of the voltages V_2 and V_1 (fig. 6):

$$\frac{V_2}{V_1}=\frac{RR_2}{R+R_2}\cdot S\cdot\left[\frac{1}{\sqrt{1+\left\{\frac{1}{\omega C_3(R+R_2)}\right\}^2}}\right]. \quad (5)$$

For frequencies at which $\omega C_3\ (R+R_2) \gg 1$, the term between the square brackets is practically 1, but for lower frequencies it is less than 1 and is frequency-dependent.

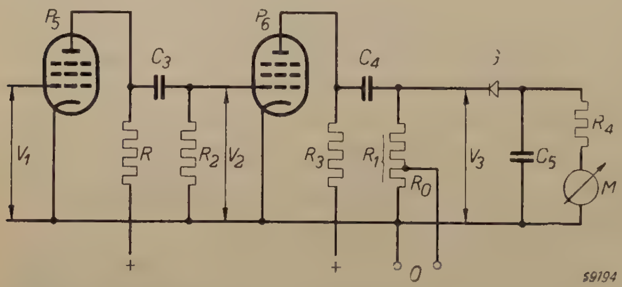

Fig. 6. The last and last but one amplifying stages and the rectifying circuit (the direct-current sources and the elements which are only of importance at high frequencies have been omitted). P_5 = fifth, P_6 = sixth amplifying valve, C_3 and C_4 = coupling capacitors, C_5 = smoothing capacitor, G = crystal detector, R and R_1 = anode resistors, R_2 = grid leak, R_3 = anode supply resistor of P_6, R_4 = series resistor of the moving-coil meter M, R_0 = the part of R_1 to which the terminals O are connected. The relaxation times C_3R_2 and C_4R_3 determine the shape of the frequency characteristic at low frequencies.

The lower frequency limit, at which V_2/V_1 has a still admissible value less than 1, can in principle be fixed as low as desired by giving C_3 and $R+R_2$ sufficently large values. Neither of these, however, can be raised indefinitely. C_3 is limited because a larger capacitance requires a capacitor of larger dimensions having a greater capacitance with respect to the surroundings; in that case an excessive lowering of the lower frequency limit would be accompanied by a lowering of the upper frequency limit. And as regards $R+R_2$ the value of this is limited by the maximum permissible value of the grid resistance R_2 (1 megohm in the case of the valve EF 42); the resistance R, which, as we have seen, amounts to no more than 400 ohms, is unimportant in this respect.

Similar considerations hold for the last stage. Again denoting the input voltage of the last valve by V_2 and the output voltage (across R_1, fig. 6) by V_3, then, in analogy with formula (5), we have:

$$\frac{V_3}{V_2}=\frac{R_1R_3}{R_1+R_3}\cdot S\cdot\frac{1}{\sqrt{1+\left\{\frac{1}{\omega C_4(R_1+R_3)}\right\}^2}},$$

where R_1, R_3 and C_4 take the place of R, R_2 and C_3. R_1 has the afore-mentioned value of about 500 ohms and is thus of little consequence in comparison with the resistor R_3 via which the anode of P_6 is fed, the value of which may be for instance 10,000 ohms but not much more in view of the D.C. voltage drop occurring in this resistor.

In the main, therefore, the deviation from the nominal amplification at low frequencies is determined by the relaxation times C_3R_2 and C_4R_3. With

C_3 in the order of 1000 pF,
C_4 in the order of 0.1 μF,
R_2 in the order of 1 MΩ and
R_3 in the order of 10 000 Ω

the apparatus has the characteristic represented by curve I in fig. 5, which at 1000 c/s deviates from the nominal level by only a few percent.

Stabilizing the amplification

The total amplification is proportional to the continued product of the mutual conductance of the six amplifying valves. Without special measures being taken the amplification would therefore depend greatly upon factors affecting the mutual conductance, i.e. the amplitude of the supply voltages and the emissive power of the cathodes.

To get a practically constant amplification we have started from the fact that the mutual conductance of a valve is strongly correlated with the mean value of the cathode current, so that as far as the mutual conductance is concerned it is immaterial, to a first approximation, whether a certain mean cathode current is obtained with a strongly negative control-grid voltage and a high screen-grid voltage or with a slightly negative control-grid voltage and a low screen-grid voltage. It is therefore a matter of keeping the mean cathode current constant. With this in view a strong direct-current feedback has been provided (24-fold per stage) by means of cathode resistors of exceptionally large value (2700 ohms; with the EF 42 resistors of 160 ohms are normally used). Each of the cathode resistors is shunted by a large capacitor, so that for alternating voltages with frequencies higher than 1000 c/s the feedback is inactive and, as a consequence, in the measuring range the alternating-voltage amplication is not thereby reduced.

Since the voltage drop in these cathode resistors is much greater than the bias required in the control-grid circuits, an adequate positive direct voltage is also applied to these circuits so that the right bias is obtained. This positive direct voltage is

derived from the supply unit via a potentiometer and kept constant with a stabilizing tube (type 85 A1).

As a result of these measures the cathode current of the EF 42 valves and thus also their mutual conductance undergo but little change as a consequence of fluctuations in the supply voltage or the ageing or replacement of the valves. With a mains voltage fluctuation of 5% the variation in the total amplification is likewise 5% (in the opposite sense). This remaining inconstancy of the amplification is due to the fact that the point from which we started, as already remarked, is only approximately correct: the mutual conductance depends mainly but not exclusively upon the mean cathode current.

The potentiometer just referred to, which is adjustable by means of a small screw sunk into one of the side panels of the cabinet, allows the calibration to be restored, if necessary, by adjusting the bias in all six grid circuits simultaneously when calibrating. In the event, for instance, of one of the valves being replaced by another with a 5% higher mutual conductance, then the corresponding increase of the amplification is compensated by reducing the mutual conductance of the other five valves by 1%; this requires only a slight alteration of the bias.

Noise

In the designing of an amplifier with such a wide frequency band as that in the present case attention has to be given to the noise.

In an amplifier there are two kinds of elements forming a source of noise: resistors and valves. Let us first take the valves.

For the R.M.S. value V of the noise voltage at the input of a valve in a frequency interval Δf we have [2]):

$$V = \sqrt{4\,k\,T\,R_{eq} \cdot \Delta f}\,,$$

where k is the Boltzmann constant $= 1.38 \times 10^{-23}$ J/°K, T is the temperature in °K and R_{eq} is the equivalent noise resistance of the valve at room temperature. For the EF 42 valve $R_{eq} = 750$ ohms. With $\Delta f = 30 \times 10^6$ c/s we find $V = 19$ μV. Thus the noise of the valve in the first stage can be reckoned with as a noise voltage of 19 μV at the input of the first stage; likewise the noise of the second stage can be reckoned with as a noise voltage of the same value at the input of this second stage. The latter, in the case of a three-fold amplification per stage, is equivalent to $19/3 = 6.3$ μV at the input of the first stage. Thus the noise of these two valves together corresponds to a noise voltage of $\sqrt{19^2 + 6.3^2} = 20$ μV at the input of the first stage. The noise contribution of the third and later valves is so small that it can well be ignored.

Similarly, in regard to the noise of the resistors in the amplifier, in the first instance we need only reckon with the resistance at the input of the amplifier. This resistance (the grid resistance of the first valve) amounts to 1 megohm, which in itself would yield a considerable noise voltage were it not for the fact that the input capacitance of the amplifier (about 20 pF) is shunted across the resistance. This capacitance together with the resistance forms a voltage divider which particularly attenuates the noise-voltage components with high frequencies. It is due to this that the remaining noise voltage originating in this resistance is small compared with the voltage of 20 μV for which the valves are responsible. The noise voltage of 20 μV causes a deflection of the meter which is only 2% of the full deflection (1 mV); this is so little that it can easily be compensated by sending through the moving-coil meter a weak counteracting direct current, which is drawn from the supply unit.

Use of the amplifier for other purposes

Since the amplifier with a characteristic like that of fig. 5 (I) can render good service for all sorts of purposes, the amplifier of the meter GM 6006 is provided with output terminals (O, fig. 6) from which a part of the output voltage can be taken. With an input voltage of 1 mV the voltage at O is 0.5 V. The resistance R_0 between the terminals O has a low value (180 ohms), so that fairly low impedances can be connected at O without causing any appreciable drop in the voltage. The meter continues to indicate the value of the input voltage.

The rectifying circuit

Choice of the detector

As already stated, the output voltage from the amplifier is rectified and the resultant direct voltage is fed to a moving-coil meter (fig. 6). A smoothing capacitor (C_5) is used, so that it is actually the peak value of the alternating voltage that is measured. The scale, however, is calibrated for the root-mean-square value of a sinusoidal voltage. Also when the voltage applied is not sinusoidal the peak value of this voltage is $\sqrt{2}$ times that of the meter reading.

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[2]) See for instance M. Ziegler, Noise in amplifiers contributed by the valves, Philips Techn. Rev. 2, 329-333, 1937.

For the detection either a diode or a crystal detector (e.g. with germanium crystal) can be used. The latter has been chosen for the following reason.

The mere fact of a diode occurring in a circuit immediately causes some current to flow through that circuit even if no voltage source is connected to it. The value of this zero current is greatly dependent upon the temperature of the cathode (and thus upon the mains voltage.) It is therefore not easy to compensate the zero current without repeated readjustment. Only when there is a fairly large voltage in the diode circuit (at least 3 to 4 V for full deflection) is little trouble experienced from the zero current. With a crystal detector, on the other hand, there is no zero current. Nevertheless also in this case it is advisable to work with not too low a voltage, with a view to the reproducibility of the characteristic at small voltages. For full deflection 1.5 V is sufficient. With the same sensitivity the amplification in this case can thus be two to three times as small as in the case of a diode.

Overloading

With an input voltage of 1 mV at the amplifier a current of 100 μA flows through the moving-coil meter. When the input voltage is increased a state of overloading of the last valve is very soon reached, where the output voltage rises less than proportionately with the input voltage and finally approaches a constant level. The rectifier current thereby increases up to about 400 μA, a value which both the meter and the crystal can well withstand (in contrast to a thermocouple, for instance, which, although it is otherwise a useful instrument for converting the output alternating current of an amplifier into a direct current, has the great disadvantage of not being able to withstand overloading). There is, therefore, no risk of the instrument being damaged through overloading, unless it were to be connected direct to a voltage of several hundreds of volts without an attenuator, when the input resistor might become too hot or the input grid capacitor break down; this does not occur, however, until the overload exceeds a hundred thousand times the nominal rating!

Internal calibration

With the left-hand switch (fig. 1) in the position "Contr." an alternating voltage of 1 mV is put across the input of the amplifier, so that there should then be a full deflection of the meter. Any deviations can be corrected by means of the method already described for adjusting the bias of the amplifying valves.

The calibrating voltage of 1 mV is obtained by causing the amplifier to oscillate, this being done by connecting to the output a tuned circuit and feeding back to the input of the amplifier (*fig.* 7)

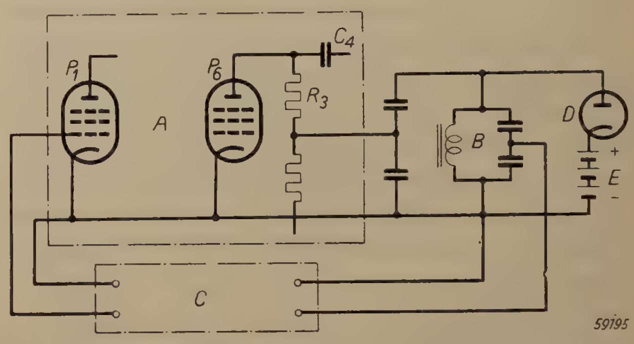

Fig. 7. Calibrating circuit. Part of the voltage across the tuned circuit *B* which is connected to the output of the amplifier *A* is fed back via a network *C* to the input of the amplifier *A*. This feedback makes the circuit oscillate. Through the action of the diode *D* the amplitude of the voltage across *B* is limited to the constant value *E*, which is so chosen that the input voltage of *A* is exactly 1 mV. R_3 and C_4 are as in fig. 6.

an exactly fixed fraction of the voltage of that circuit in the right phase. When the amplifier is switched on there arises in the tuned circuit an increasing alternating voltage which is checked by a diode in series with a direct voltage source (threshold voltage) shunted across that circuit. So long as the peak of the alternating voltage is smaller than the threshold voltage the parallel branch has no effect, but as soon as the peak exceeds the threshold voltage the tuned circuit is heavily damped. The result is that the voltage amplitude of the circuit is limited to (practically) the threshold voltage. The latter (about 7 V) is obtained by voltage-division from the constant voltage of the stabilizing tube already mentioned (85 A1).

The frequency of the oscillation is about 5000 c/s, thus being in a range in which the amplification does not depend upon frequency (see fig. 5).

The tuned circuit has a high quality factor (impedance 3 megohms); the coil has a core of "Ferroxcube".

The attenuator

For measuring voltages higher than 1 mV use is made of an attenuator preceding the amplifier. The impedance of this attenuator together with the input impedance of the amplifier forms a voltage divider. For frequencies above 25,000 c/s the latter impedance is almost purely capacitive. By using a capacitor for the attenuator one therefore

gets an attenuation which in this range is practically independent of the frequency. Below 25,000 c/s, however, the lower the frequency the more the input impedance of the amplifier assumes the character of a resistance, so that the attenuation then becomes frequency-dependent (see curve *II*, fig. 5).

The attenuator of the voltmeter GM 6006 (*fig. 8*) consists of a capacitor which is variable in twelve steps and with which the following degrees of sensitivity can be obtained: full deflection at 1 mV, 10 mV, 31.6 mV, 0.1 V, 0.316 V, 1 V, 3.16 V, 10 V, 31.6 V, 100 V, 316 V, 1 kV. The size of the steps is therefore a factor $\sqrt{10}$, except for the first step, the size of which is a factor 10. The attenuator is made in the form of a sliding capacitor and is mounted in a "probe" connected to the amplifier by means of a cable.

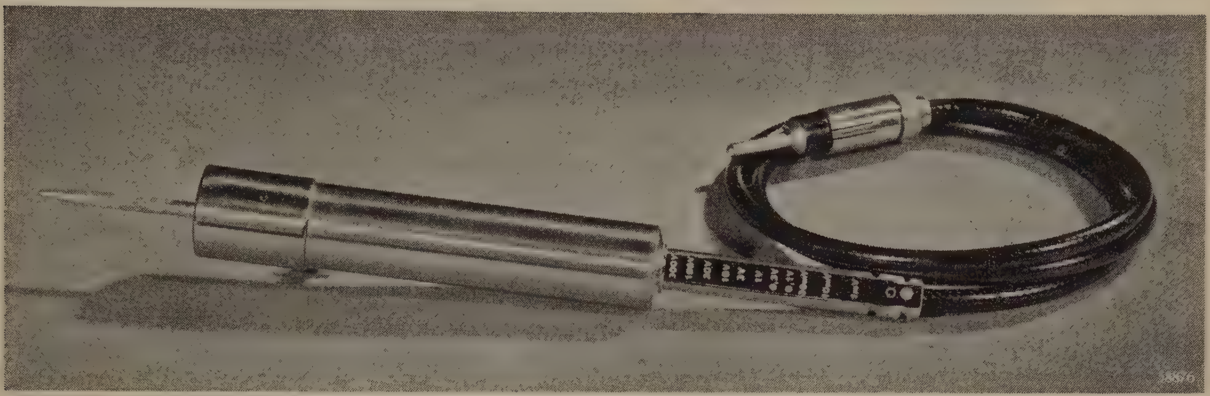

Fig. 8. Capacitive attenuator with cable. The rod slides in and out to vary the sensitivity. The maximum sensitivity corresponds to 1 mV and the minimum to 1 kV for full deflection. Stops hold the rod in each of the 12 positions.

The fixed electrode of the sliding capacitor is connected to an external contact pin and the sliding electrode to the core of the cable. The sliding electrode is fixed in each of the 12 positions by a stopping device. The position is read from a graduated scale following the movement of the sliding electrode (fig. 8; the number 31.6 is rounded off on this scale to 30, 0.316 is rounded off to 0.30, and so on).

The aim has been to construct the capacitor in such a way that the successive positions each differing in sensitivity by a factor $\sqrt{10}$ [3]) are obtained by equal movements of the slide, since then the influence of a given inaccuracy is constant at each stop. This implies that the capacitance between the electrodes must be an exponential function of the distance between those electrodes. This has been reached in the following way.

If two disc-shaped electrodes are placed in an earthed tube (*fig. 9*) and the distance l between the electrodes is at least several times the diameter D of the tube, then as l increases the capacitance between the electrodes diminishes approximately exponentially.

The configuration illustrated in fig. 9 may be regarded as a wave guide. Waves which are longer than a certain critical wavelength cannot be propagated through a wave guide [4]); the amplitude of such waves decreases exponentially with the depth to which the wave has penetrated into the pipe [5]).

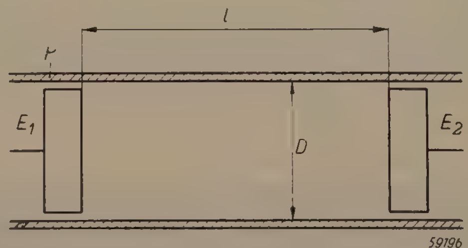

Fig. 9. The capacitance between two electrodes (E_1, E_2) in an earthed tube P is to a good approximation an exponential function of the distance l, provided l is at least several times as large as D.

To change the capacitance by a factor 10 an axial displacement of 0.48 D is required. When, however, the electrodes are brought so close together that $l \approx D$, or $l < D$, the capacitance is also strongly influenced by the shape of the electrodes.

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[3]) The position for 1 mV, where the electrodes are short-circuited, is not considered here.

[4]) See for instance W. Opechowski, Electromagnetic waves in wave guides, II, Philips Techn. Rev. **10**. 46-54, 1948 (No. 2), in particular page 52.

[5]) A mechanical model with which this can be demonstrated for rectangular wave guides was recently described by K. S. Knol and G. Diemer in "A model for studying electromagnetic waves in rectangular wave guides", Philips Techn. Rev. **11**, 156-163, 1949 (No. 5), figs. 4 and 5.

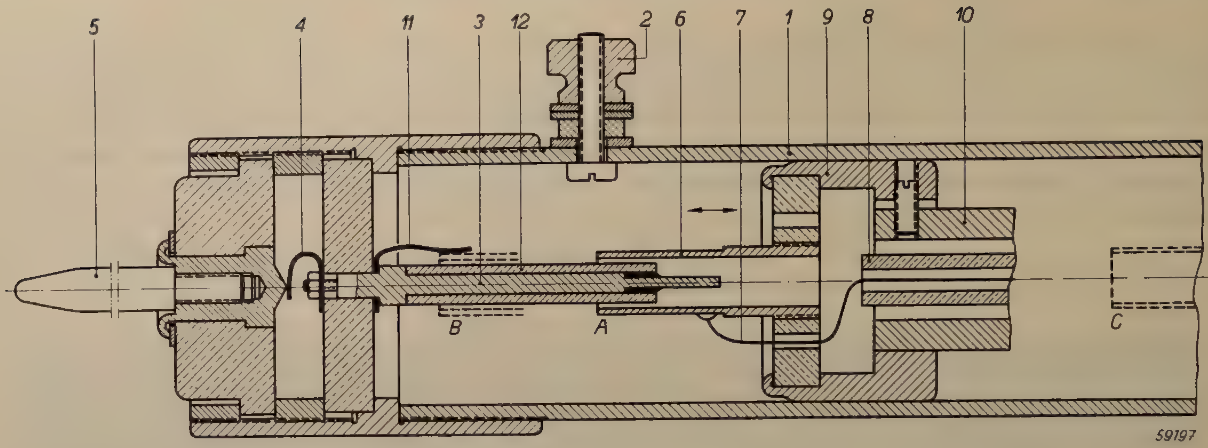

Fig. 10. Longitudinal cross section of the capacitive attenuator (slightly simplified; about 1.6 times the actual size). *1* = metal tube that has to be earthed by means of the screw *2*. *3* = fixed electrode connected via the leaf spring *4* to the contact pin *5*. *6* = tubular sliding electrode connected to the core *7* of the cable *8*. *6* is attached with intermediate insulation to the piston *9* in the tube *1*. The piston is attached to a rod *10* which is extended outside the tube *1* and which is marked with a calibrated scale (see fig. 8); acting upon this rod is a stop not shown in the illustration (a small steel ball pressed into a hole by a spring). The position *A* of the sliding electrode is that for 30 mV. The dotted lines at *B* indicate one extreme position (1 mV), in which the spring *11* short-circuits the attenuator. In the position indicated at *C* the distance between the electrodes is so great that the exponential law applies. To get approximately the same law also in a position like that at *A* the ceramic tube *12* has been fitted in and the fixed electrode given a thin and a thick part.

For low sensitivities (voltage to be measured between 1 kV and approx. 1 V) the distance between the electrodes in the attenuator is such that the exponential law applies. In order that this law may also apply to a good approximation for higher sensitivities, the electrodes have been given a special shape: the sliding electrode is tubular and in the positions for high sensitivity it slides concentrically round the rod-shaped, fixed electrode. To approximate the right variation in capacitance the fixed electrode is enveloped by a small ceramic cylinder and is thin at one end (see *fig. 10* representing a cross section of the attenuator); this does not affect the exponential variation for low sensitivities (great distance between the electrodes).

As may be seen from fig. 8, the graduation of the scale in steps of $\sqrt{10}$ has indeed in this way been made practically linear in sensitivity.

In the position for the highest sensitivity (1 mV) a contact spring provides for the short-circuiting of the electrodes. (When measuring with this sensitivity, however, it is better to make a direct connection to the terminals of the amplifier, thereby avoiding the capacitance of the cable). In the other positions the input capacitance of the attenuator with respect to earth is only 2.8 pF.

Even the slighest displacement of the fixed electrodes with respect to the sliding one would upset the calibration. Therefore, in order to avoid derangement of this electrode in the event of something knocking up against the contact pin the electrical connection between the fixed electrode and the contact pin is brought about by means of a weak spring (fig. 10).

In the cable connecting the attenuator to the amplifier, and which is 0.85 m long, owing to the presence of self-inductance and capacitance there would be a tendency, at the highest frequencies, to a certain boosting of the voltage, in consequence of which the voltage at the amplifier end of the cable would be higher than that at the beginning. The effect has been neutralized by shunting a suitably chosen damping resistor across the input of the amplifier.

Summary. A description is given of a millivoltmeter for a wide frequency range (10^3-30×10^6 c/s) which gives full deflection at an input voltage of 1 mV and with the aid of an attenuator has been made suitable for measuring voltages from 1 mV up to 1000 V. Incorporated in the apparatus is an amplifier with six EF 42 valves and an amplification factor of 1500, to which a moving-coil meter is connected via a crystal detector. In the amplifier special measures have been taken to get an amplification that depends as little as possible upon frequency, fluctuations in mains voltage and ageing of the valves. For the purpose of calibration the amplifier is made to oscillate, thereby setting up across the input an alternating voltage of 1 mV (fixed by a constant threshold voltage), so that the meter should then give the full deflection; any deviations are corrected by readjusting the bias at the control grids. The instrument can withstand heavy overloads. The attenuator is connected to the amplifier with a cable and consists of a sliding capacitor of special construction with 12 calibrated positions; it is of such a construction that with the same displacement the sensitivity changes by the same factor in each step. The amplifier can serve also for other purposes for amplifying 500 times an alternating voltage smaller than 1 mV.

AN APPLICATION OF GEIGER COUNTER TUBES FOR SPECTROCHEMICAL ANALYSIS

by O. G. KOPPIUS *).

621.385.842:545.82

It has long been known that Geiger counter tubes, using the photoemissive effect of the cathode metal, can be applied to the measurement of very feeble visible or ultraviolet radiation. As a direct indicating instrument for measuring radiation intensities, the counter tube could be expected to offer special advantages in the detection of traces of chemical elements by their characteristic spectral emission lines. A simple apparatus based on this principle was designed and for several years successfully utilized for the detection of lead in the atmosphere of industrial areas.

The detection of traces of an element by means of its characteristic spectral lines emitted in an electric arc or spark is rather old. Kirchhoff and Bunsen used this principle first in the isolation and discovery of caesium and rubidium; Gerlach established the so-called "internal standard method" which enabled the principle to be used for precise quantitative analyses. In the last decade many industrial applications have been made, for example in the routine analysis of iron and steel for calcium, silicon, manganese, chromium, magnesium, and other elements. With modern equipment, the method is capable of high speed and precision [1]).

The application of spectrochemical analysis which will be described in this article concerns the detection of lead in air. Atmospheric contamination by lead may occur in several branches of the chemical industry, due to small leaks in plant installations. Because of the well known toxic effect of lead, a maximum permissible lead concentration in air has been established in several countries. To make sure that the lead concentration in a plant does not exceed the limit of safety, a rapid means of analyzing air samples for lead is desirable.

When the problem presented itself in one of the E. I. du Pont de Nemours plants, spectrochemical analysis, because of its specificity and sensitivity, was considered to offer the best prospects for meeting the rather exacting requirements. A photographic technique was developed for the purpose [2]). In the plant where the purity of the air was to be examined, an electric spark was run continuously between two copper electrodes. The spectrum of the spark was photographed with the aid of a small quartz spectrograph. Part of the spectrum, consisting principally of copper lines, with a certain number of other lines attributable among other things to the water vapor content of the air, is shown in *fig. 1a*. If the air contains traces of a lead compound this is decomposed in the hot spark, and lead lines will appear in the spectrum. The most sensitive line, i.e. the line which appears at the lowest lead concentration, is the line at about 2203 Å,

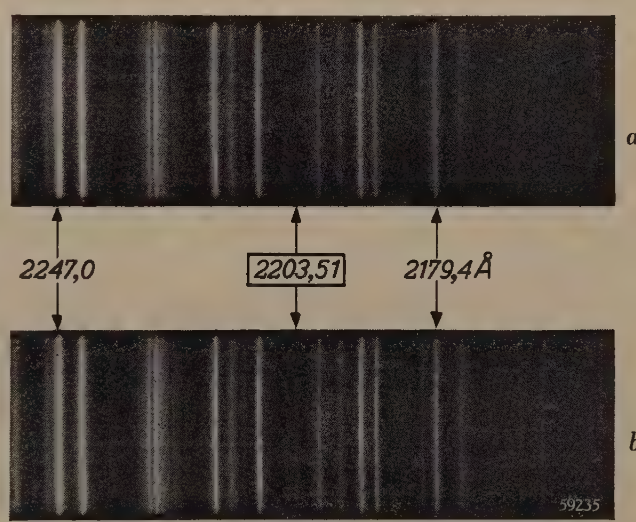

Fig. 1. *a*) Spectrum of the spark discharge in the absence of lead. Most lines are due to the copper of the electrodes, a few are caused by the water vapor content of the air.
b) Spectrum of the spark in lead contaminated air, showing the lead line at 2203 Å.

i.e. well up in the ultraviolet. A photograph of the copper spark spectrum with this lead line is shown in fig. 1*b*. Inspection of the photographic plate for the presence of this line enabled a lead concentration as low as one part in 50 million (on a weight basis) to be detected. This is about 7 times lower than the maximum permissible concentration of 0.15 mg lead/m^3 air. The exposure time required

*) Philips Laboratories, Inc., Irvington on Hudson, N.Y., U.S.A.

1) Cf. for example R. Sawyer, Experimental Spectroscopy, Prentice Hall, New York 1944.

2) H. Aughey, J. Opt. Soc. Amer. **39**, 292-293, 1949 (No. 4).

was about one minute. An approximate quantitative analysis was possible by comparing visually the intensity of the lead line with that of adjacent copper lines. Calibration was accomplished by comparison with chemical analyses performed on samples taken simultaneously from a common air stream.

Although the photographic method worked quite satisfactorily and the superiority of spectrochemical analysis over previously used chemical methods was striking enough, still its application was hampered by the fact that the method was essentially discontinuous. In the operation of a plant, safety measures should be based, not on the detection of too high a lead concentration in one place, but rather on the early discovery of an increase in the lead concentration as a function of time, revealing the presence of a leak in plant installations before dangerously high lead concentrations in the atmosphere are attained. Detecting such a trend of the lead concentration to increase and locating the leak by the photographic method lines which is given by the spectrograph can be dismissed (except for alignment and calibration purposes). The important advantage of the Geiger counter tube, provided with means for directly measuring the rate of arrival of the radiation quanta, lies in its being a continuously working, direct reading device. Such a device can serve the purpose of leak detection much better than any discontinuous method, as it will immediately reveal the trend of variation in the lead concentration. Thus, if the air to be analyzed is pumped to the spark gap by means of a long flexible hose with which the operator can scan pipes, valves etc. of an installation, a very effective method of leak hunting is obtained.

For reasons to be explained later, the Geiger counter method in the present case is not capable of a similar sensitivity and accuracy as the photographic method. However, for the restricted objective of locating areas of high lead concentration at possible leaks in plant installations, performance requirements are less severe and the Geiger counter method fully proved its ability to comply with them.

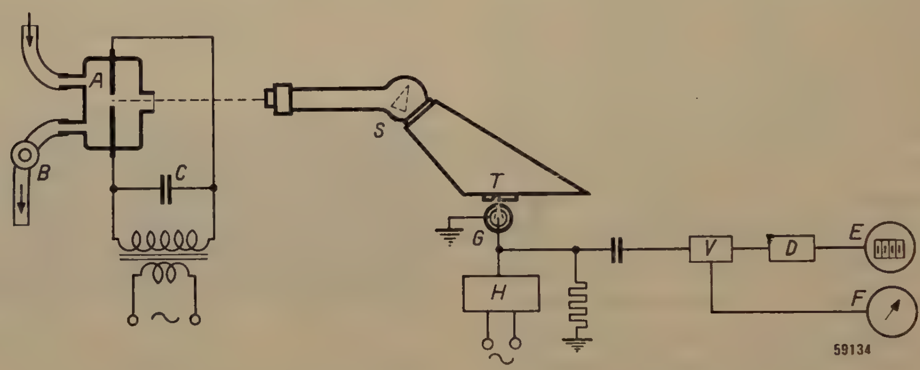

Fig. 2. Apparatus for the detection of lead. The spark *A* between copper electrodes, condensed by a capacitor *C*, excites the lead contained in the air pumped through the spark housing by the blower *B*. The radiation emitted by the spark is dispersed by the spectrograph *S*; the adjustable exit slit *T* isolates the lead line 2203 Å, which is measured by the Geiger counter tube *G*. *H* is the high voltage supply for this tube. The discharges triggered in the tube are amplified in *V* and counted by the scale-of-8 *D* and the mechanical register *E*. The deflection of the mA-meter *F* is proportional to the frequency of the discharges.

involved a number of successive samplings and exposures. In general, one to three hours was required before any resulting data could be utilized.

Considerable improvement was achieved by substituting a photoelectric Geiger counter tube for the photographic plate [3]) as a means for detecting the energy of the spectral line at 2203 Å. In fact, this line, if isolated by a spectrograph, can be measured by a radiation detector, such as the Geiger tube, and the information concerning other spectral

A few details of the apparatus used, which was constructed for E. I. du Pont de Nemours & Co. by Philips Laboratories at Irvington, N.Y., are described here [4]).

The complete set-up is shown in *figs 2* and *3*. A slit which can be moved across the spectrum is mounted in the focal plane of the quartz spec-

[3]) The application of Geiger counter tubes to spectrochemical analysis was initiated by O. S. Duffendack and W. E. Morris, J. Opt. Soc. Amer. 32, 8-24, 1942.

[4]) A short description was published earlier in: O. G. Koppius, J. Opt. Soc. Amer. 39, 294-297, 1949 (No. 4). — The author wishes to express his appreciation to Mr. H. Aughey of the E. I. du Pont de Nemours & Co. for his valuable assistance in this work.

trograph which disperses the radiation from the spark source. The position and width of the slit are adjusted so as to let only the 2203 Å lead line pass.

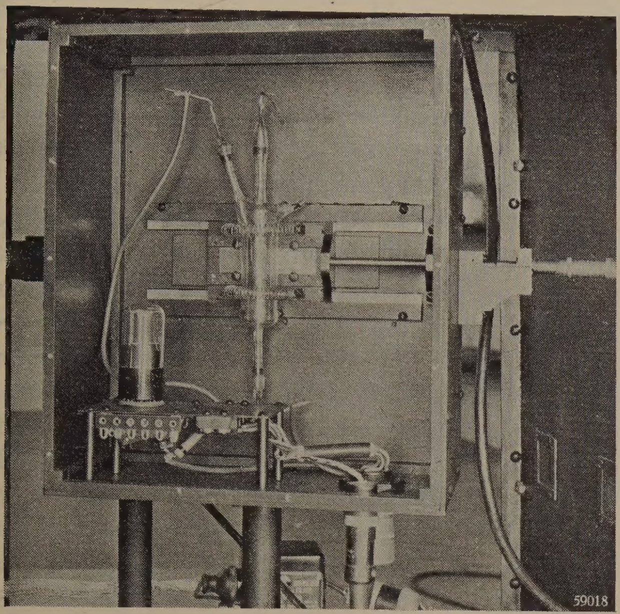

Fig. 3. Photograph of exit slit assembly with Geiger counter tube and preamplifier, at the back of the spectrograph. By the micrometer screw at the right the slit position in the spectrum may be adjusted.

The Geiger counter tube is placed behind the slit. Between the axial wire anode and the surrounding cylindrical cathode of this tube a voltage of about 1500 V is applied. Short discharge pulses are triggered in the tube by the photo-electrons liberated from the cathode metal by the ultraviolet radiation impinging on the inside wall. The radiation enters the cathode cylinder through a rectangular slot cut lengthwise in the wall as shown in *fig. 4*. The discharge pulses are amplified and fed to a mechanical counter or to a circuit measuring the rate of arrival of the quanta at the counter tube by the mean value of a current. The circuits used for this purpose are similar to those used in the Geiger counter X-ray spectrometer described earlier in this Review [5]).

The deflection of the rate meter milliammeter provides a direct check on the lead concentration at the place where the air is pumped off to the spark. It is possible to make a continuous record of this concentration if desired, or to make the instrument sound an alarm as soon as the lead content exceeds a given limit. The whole apparatus including the power supplies is mounted on wheels so that every part of the manufacturing area can be surveyed. The spectrograph and the counter tube with a pre-amplifier are mounted in an airtight box in which an inert atmosphere can be maintained, in case the air of the area to be examined should contain some inflammable vapor. The spark source is mounted in an air duct which traverses the airtight box. Air is forced through the duct by a small fan driven by an explosion-proof motor. To prevent a "flash-back", which may occur in case of an explosion, fire screens are mounted on the intake and outlet of the air duct.

The fact that the Geiger tube in this application serves as a photo-electron counter entails several peculiarities in its design not encountered in the more common counter tubes intended to respond to electrons, gamma-rays or X-rays. In X-ray applications, for instance, the counter tube must be designed to absorb the entering X-rays in the gas volume between the electrodes, the absorbed X-ray quanta setting electrons free (cf. the article quoted in[5])) ; the choice of the electrode metal is not important in this case. In the photo-electron counter, however, the gas filling must be chosen so as not to absorb any of the entering ultraviolet radiation quanta, because such an absorption would not in all cases give rise to a discharge pulse, and the cathode must be made of a metal giving a strong photoemissive effect. In our case a very pure (O.F.H.C.) copper cathode, cleaned by prolonged heating in hydrogen, was used. The energy necessary for liberating an electron from this metal amounts to $E = 4.42$ electronvolt; hence, according to Einstein's law, the maximum wavelength capable of liberating

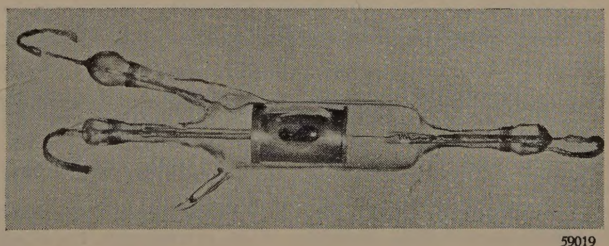

Fig. 4. Quartz Geiger counter tube used for detection of radiation at 2203 Å.

an electron, given by $\lambda = ch/E$($c =$ velocity of light, $h =$ Planck's constant) is about 2800 Å. This shows that the counter tube will be sensitive in the spectral region with which we are concerned. The anode is a tungsten wire 75 μ in diameter. The electrodes are mounted in an envelope of clear fused quartz and the tube is filled with argon at a

[5]) J. Bleeksma, G. Kloos and H. J. Di Giovanni, X-ray spectrometer with Geiger counter for measuring powder diffraction patterns, Philips Techn. Rev. 10, 1-13, 1948 (No. 1).

pressure of 20 cm Hg. A small amount of alcohol vapor is added for rapidly quenching the discharge (cf. [5])). Neither of these gases absorbs the 2203 Å line to an appreciable extent. The counters have proved very reliable during their rated lifetime, so that during the past three years the instrument has been kept in almost continuous operation.

In the spectrograph (a Hilger E3), the rays of every wavelength converge onto their respective places in the focal plane in beams comprising an angle of about 10 to 30°, while the focal plane itself is situated obliquely to these beams; cf. *fig. 5*. As a consequence the radiation of the line 2203 Å, passing through the slit, is contained in a beam of a rather unfavorable configuration to be caught in the counter tube. A simple solution for this difficulty, avoiding the necessity of a rather artificial tube design, was found by mounting a mirror of stainless steel on the back of the slit, in the manner shown in fig. 5. When the angle of the mirror is adjusted to a suitable value, all the radiation passing through the slit is reflected into the hole of the counter cathode. The reflectivity of steel (and most other materials) for the ultraviolet radiation of 2203 Å is rather poor at normal incidence, but at near grazing angles of incidence as occur in our case, practically complete reflection of the radiation is obtained.

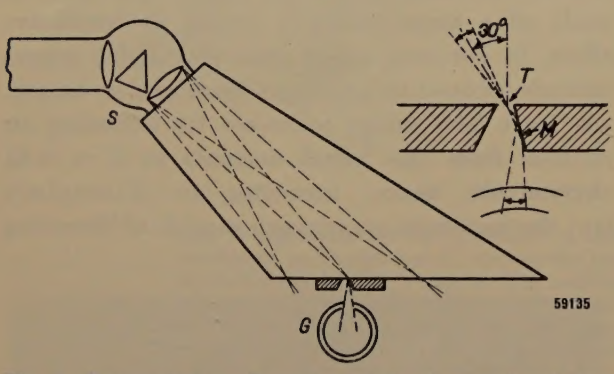

Fig. 5. Geometrical configuration of the beam of radiation of 2203 Å arriving at the exit slit of the spectrograph. By a mirror M of stainless steel mounted on the back of the slit, the entire beam is reflected into the hole of the counter tube cathode.

Once in several months it is necessary to scan the spectrum on either side of the lead line 2203 Å for readjustment of the slit. The adjacent copper lines are easily located, whereupon the slit is set on the lead line position by a simple interpolation. Of course, on moving the slit across the spectrum the configuration of the beam reflected by the mirror will change to some extent. The hole in the counter tube cathode wall is made large enough to receive the whole of the reflected beam for all positions of the slit within the portion of the spectrum which it may be desired to scan. The alignment of the spectrograph with the source, of course, must be checked more frequently, viz., once or twice during an eight hour period, as it is not possible for a simple portable instrument to maintain good optical alignment for a longer period under plant conditions. Every now and then the overall stability and sensitivity of the apparatus may be checked by measuring the relative intensities of the 2200 and 2195.8 Å copper lines.

A chart of the spark spectrum, as determined by setting the slit in subsequent positions about $^1/_2$ Å apart and noting the number of counts per second, is shown in *fig. 6a*. Fig. 6*b* gives a microphotometer trace of a photograph of the spectrum taken with the same spectrograph. The resolution of lines in the two cases is almost identical and more than adequate to resolve the 2203 Å lead line from nearby copper lines. A striking difference between the two spectra is the much lower background of the counter tube trace. This is due to the fact that the counter, because of the photoelectric threshold, is not affected by scattered radiation of wavelengths longer than 2800 Å arriving at the slit, whereas the photographic plate responds to this radiation.

The low background sensitivity of the Geiger counter tube is important, both for a practical and a fundamental reason.

In the photographic method, where the whole spectrum is recorded, the background contribution to the plate density can be recognized as such on inspection of the plate and appropriate corrections made. So the background does not prevent a very feeble line from being observed, and after corrections for the background have been applied a fairly accurate quantitative evaluation of the lead concentration from the relative line intensities is possible.

With the direct indicating Geiger counter method, however, no information is available during normal operation as to whether the measured number of counts per second is due to the lead line or to the background. The presence of the lead line must be derived and its intensity (L) evaluated by subtracting a constant number of counts (B), ascribed to the background and obtained as a result of a zero experiment, from the total number ($B+L$). In view of the statistical character of the arrival of radiation quanta at the counter tube, this total number contains a probable error $\sqrt{B+L}$, which in full is transmitted to the result, L, of the subtraction. The relative error $\sqrt{B+L}/L$ can be made small enough only by prolonged

counting. Obviously the necessary counting time for a given accuracy will be shorter the smaller the background intensity B. This will be especially important when the counting rate (intensity L) is low.

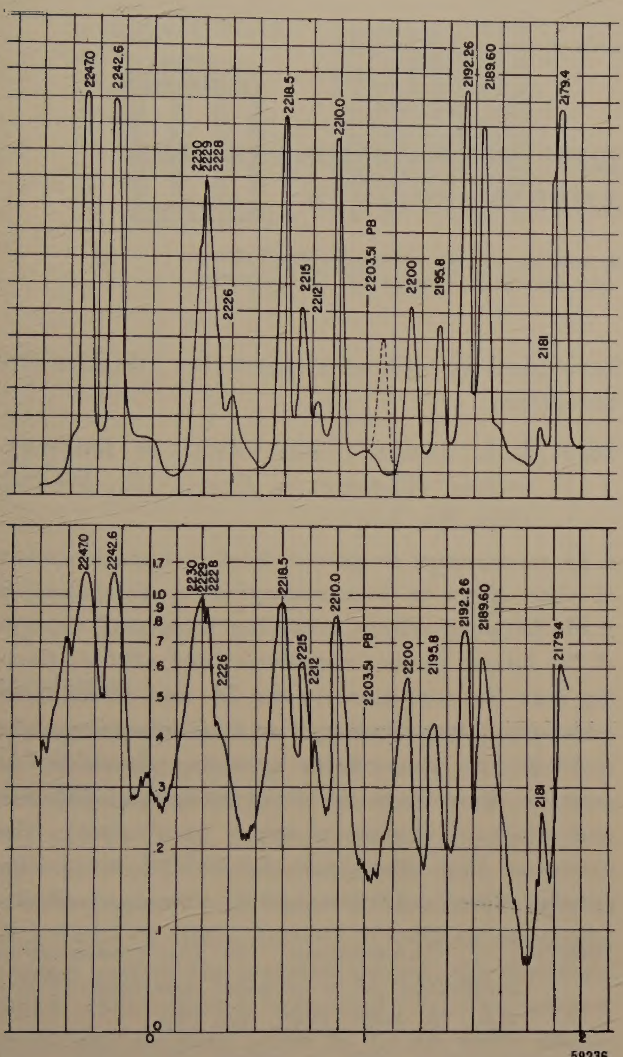

Fig. 6. *a*) Copper spectrum, determined by measuring the number of counts per second for a large number of positions of the exit slit (about $^1/_2$ Å apart). The position of the lead line 2203 Å is indicated by a dotted line.
b) Microphotometer trace of copper spectrum obtained photographically.

This is a practical consideration. A fundamental one is that, in reality, even the statistical mean value B is not a constant; the background is subject to continuous changes due to the erratic behaviour of the spark discharge. These changes have much more influence with the Geiger tube than with the photographic plate, owing to the shorter averaging time. By the uncertainty of the value of B to be subtracted, a lower limit of the detectable lead concentration is imposed. So it may be said that the low background sensitivity of the counter tube is chiefly responsible for the comparatively high lead sensitivity of the apparatus. The lower limit of detectability, in a single measurement, is about 0.6 mg lead per m^3 air, or 1 part in about 2 million on a weight basis. Although this sensitivity cannot compete on equal terms with that of the photographic method, it is fully adequate for the purpose of leak hunting, where the discovery of local variations in lead concentration is all-important.

Several years' experience has shown the inherent soundness of the method for the detection of lead. However, it should be emphasized that in the construction of the apparatus there is little that points to its specificity for lead. The flexible hose and other tubing are made of "Saran" (a plastic) instead of rubber because certain lead compounds have a high affinity for rubber. The mirror behind the slit is specifically adjusted for the 2203 Å position of the slit. Apart from these minor details, there appears to be no fundamental reasons why the instrument could not be used for the detection of other elements, provided these elements show a sensitive emission line in a suitable spectral region and the slit is placed in the correct position. The analysis of dusts for elements such as arsenic, barium and beryllium are suggested examples.

Using a more constant source and a more elaborate technique, spectrochemical analysis with the Geiger counter is also feasible in cases where accurate quantitative data are required, as was shown in recent publications concerned with the analysis of the phosphor content of steel [6]). The background difficulties mentioned previously can be obviated by a method of "internal control", similar to the one used in the photographic procedure: by using two Geiger counter detectors it is possible to measure the ratio between the intensities of the lead line and an adjacent copper line, and thereby average out fluctuating background. Though, in some situations, also in our case accurate quantitative data may be desired, the method of internal control was discarded in the instrument described, as it would have unnecessarily complicated the instrument for the purpose of leak hunting; in a specific case it is easy enough to obtain quantitative information from a photographic recording of the spectrum.

[6]) R. Hanau and R. A. Wolfe, J. Opt. Soc. Amer. **38**, 377-383, 1948 (No. 4); F. R. Bryan and G. A. Nahstoll, J. Opt. Soc. Amer. **38**, 510-517, 1948 (No. 6).

Summary. A spark discharge is maintained between two copper electrodes in the air of a plant where atmospheric contamination with lead or lead compounds can occur through possible leaks in plant installations. If lead is present the

spark will contain the lead line at 2203 Å. By a small quartz spectrograph provided with a movable slit in its focal plane, this spectral line is isolated and its intensity is measured by a photoelectric Geiger counter tube with counting rate meter. The sensitivity of the apparatus in normal operation is limited to about 0.60 mg lead per m^3 air, by the fluctuations of the background intensity emitted by the spark. Although this is more than the maximum permissible concentration of lead in the air (0.15 mg per m^3), the instrument has proved very useful as a means for detecting and locating small leaks in pipes or valves, in whose vicinity high lead concentrations may occur. The superiority of the method as compared with the usual and more sensitive photographic procedure of spectrochemical anlysis is due to the fact that the direct indicating, continuous working, radiation meter is ideal for monitoring changes in concentrations.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk can be obtained free of charge upon application to the Administration of the Research Laboratory, Kastanjelaan, Eindhoven, Netherlands.

1857: A. Bierman: A new type of betatron without an iron yoke (Nature London **163**, 649, 1949, April 23).

A new type of betatron is described in which the magnetic field is obtained by means of coils in air, through which the discharge current of a 6.5 μF condenser battery passes. There is only a small iron core, by means of which it is easy to fulfil the "flux condition". Saturation of the core effects contraction of the orbits towards the end of the acceleration period, until the electrons strike a tungsten target 0.1 mm thick. The betatron as a whole weighs no more than 50 kg, the iron core itself weighing less than 5 kg. The peak value of the magnetic induction is 0.4 Wb/m^2 (4,000 gauss), the radius of the orbit 8 cm; the energy of the accelerated electrons amounts to 9 MeV. Cf. Philips Techn. Rev. **11**, 65-78, 1949 (No. 3).

1858: J. A. Haringx: Het merkwaardig gedrag van op druk belaste schroefveren (Voordrachten Kon. Inst. Ingenieurs **1**, 298-313, 1949, No. **3**). (The remarkable behaviour of compression-loaded helical springs; in Dutch.)

A survey is given of the remarkable phenomena demonstrated by compression-loaded helical springs in respect of their elastic stability, lateral rigidity and natural frequencies for transverse vibrations. The existence of these phenomena was predicted on account of a theoretical calculation which was based upon the current simplification of replacing the helical spring by an elastic prismatic rod and a new interpretation of the latter's rigidity against shearing. At the end of the paper it is shown that the respective problems had to be treated first before helical springs could succesfully be applied as resilient elements for vibration-free mountings.

1859: J. L. Snoek: Time effects in ferromagnetism (Physica 's Grav. **15**, 244-252, 1949, No. 1/2).

In an attempt to give a short systematic survey of time effect in ferromagnetism a distinction is made between effects involving structural charges of the lattice (ionic time-effects) and effects affecting only the conditions of the 3*d*- and 4*s*-electrons (electronic time-effects). The ionic effects may be divided into time-effects involving plastic deformations, time-effects involving interstitial diffusion and effects of unknown origin (in ferrites). The electronic time-effects may be divided into eddy-current effects and ferromagnetic resonance effects.

1860*: C. J. Bouwkamp: On the transmission coefficient of a circular aperture (Phys. Rev. **75**, 1608, 1949, No. 10).

In connection with an article of Levine and Schwinger on the diffraction of a scalar plane wave by an aperture in an infinite plane screen, the writer briefly indicates the derivation of the correct expression for the transmission coefficient of a circular aperture.

1861: G. W. Rathenau: Enige nieuwe resultaten op het gebied van rekristallisatie (De Ingenieur **61**, Mk 57-Mk 63, 1949, No. 20). (Some new results on recrystallization; in Dutch.)

Some recent views on recrystallization. Review of recent literature on polygonization, recrystallization and grain growth. Some new results concerning the secondary recrystallization of nickel-iron alloys are discussed.